Anisokinetic Shrouded Nozzle System for Constant Low-Flow Rate Aerosol Sampling from Turbulent Duct Flow

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An anisokinetic shrouded nozzle system was designed for sampling particles at a constant low flow rate from a ventilation duct to an aerodynamic particle sizer (APS). Shrouded anisokinetic nozzles are a means for sampling from a moving airstream with higher particle transmission than with unshrouded isokinetic nozzles. This shrouded nozzle sampling system was evaluated in an experimental ventilation duct system. Aspiration and transport efficiency measurements were made for five particle sizes in the range 1–13 \(\mu m\) at each of three duct air speeds in the range 2.2–8.8 m/s. Under these conditions, the shrouded nozzle system showed improved performance compared to buttonhook isokinetic nozzles, especially for larger particles and higher air speeds. Measured transmission efficiencies through the shrouded nozzle sampling system were generally higher and more reliably predictable than those through buttonhook isokinetic nozzles. Model predictions of transport and aspiration efficiencies of the shrouded nozzle system showed good agreement with measurements over the entire range of experimental conditions. The shrouded nozzle sampling system could be used to measure concentrations in ventilation ducts with an APS for particles in the diameter range 1–13 \(\mu m\).

[Supplementary materials are available for this article. Go to the publisher’s online edition of Aerosol Science and Technology to view the free supplementary files.]

INTRODUCTION

Accurately measuring airborne particle size distributions in ventilation ducts is useful for multiple applications, including identifying in-duct particle sources, evaluating the impact of outdoor particles on indoor air, and assessing workplace exposures. Ideally, a sample taken from the duct airstream should be unaffected by the sampling process and so exhibit the same particle size distribution as the air in the original environment. Sampling systems generally consist of an inlet, a transport line, and a particle collection or detection device. Particle behaviors at the inlet and in the transport line influence the degree to which the delivered aerosol is representative of the sampled aerosol. Shrouded anisokinetic nozzles are one means of increasing transmission efficiencies when sampling supermicron particles from ventilation ducts for delivery to a constant flow rate measurement instrument.

Bias in the concentration of particles entering the inlet is quantified by the aspiration efficiency, \(\eta_a\), defined as the ratio of the particle concentration just inside the sampling inlet plane, \(C_{\text{inlet}}\), to the concentration in the bulk flow, \(C_{\text{bulk}}\). Deposition to transport line walls is quantified by the transport efficiency, \(\eta_t\), the ratio of the particle concentration at the outlet plane of the transport line, \(C_{\text{outlet}}\), to \(C_{\text{inlet}}\). The total transmission, \(T_{\text{total}}\), through a sampling system quantifies the relationship of the delivered aerosol to the sampled aerosol:

\[
T_{\text{total}} = \frac{C_{\text{outlet}}}{C_{\text{bulk}}} = \eta_a \eta_t. \quad [1]
\]

Assuming that the mean airflow is aligned with the axis of the inlet, sampling is isokinetic when the average air speed at the inlet, \(u_{\text{inlet}}\), is equal to the local air speed in the free stream, \(u_o\) (Brockman 2001). Isokinetic sampling produces aspiration efficiencies equal to one for all particle sizes. Sub-isokinetic sampling, which causes streamlines to decelerate and diverge at the inlet, can lead to aspiration efficiencies greater than one when, owing to their inertia, particles enter sampling inlets from air streamlines that are not themselves captured. Similarly, super-isokinetic sampling can lead to aspiration efficiencies less than one when particles associated with converging streamlines are lost from the accelerating flow owing to their inertia.
When sampling from a turbulent airstream, as in a ventilation duct, sampling at the precise isokinetic air speed cannot be continuously achieved owing to the rapid and random velocity fluctuations of the turbulent flow. The best that can be accomplished is to sample with the nozzle inlet air speed equal to the local mean air speed. If the aerosol must be sampled at a constant flow rate, as is necessary for certain instruments, then isokinetic sampling from airstreams with different mean air speeds requires nozzles with different diameters. The mean air speed in a real ventilation duct may also vary with time, further complicating isokinetic sampling.

Where isokinetic sampling is not practically achievable, sampling with shrouded anisokinetic nozzles can be an effective means of delivering an aerosol to a constant low-flow sampling instrument. Previous investigators have reported advantages of shrouded anisokinetic nozzles compared to unshrouded isokinetic nozzles that include higher total transmission and lower sensitivity to changes in sampling flow rate, bulk air speed, nozzle alignment, and particle size (McFarland et al. 1989; Chandra and McFarland 1995).

A shrouded nozzle was first designed and described by McFarland et al. (1989) for continuous radionuclide aerosol sampling from an exhaust stack at a nuclear storage facility at a constant flow rate of 170 L/min. McFarland et al. performed aerodynamic testing of velocity profiles within the shroud and aerosol testing to characterize transmission and aspiration efficiencies. A similar but smaller shrouded nozzle intended for stack sampling at a constant rate of 57 L/min was designed and extensively characterized by Chandra and McFarland (1995). Experiments reported by Chandra and McFarland (1997) demonstrated the benefits of shrouded nozzles versus unshrouded isokinetic nozzles. Subsequent designs by Ram et al. (1995), Twohy (1998), and Irshad et al. (2004) were developed for aerosol sampling from aircraft. These nozzles and shrouds have diameters in the approximate ranges 15–30 mm and 52–150 mm, respectively, and were designed for sampling at high air speeds and at flow rates in the range 30–90 L/min. To our knowledge, no shrouded sampling probe has been developed for low flow rate sampling at 5 L/min as is appropriate for an aerodynamic particle sizer.

This article addresses the challenge of sampling from a duct to a measurement device at a constant flow rate by using a shrouded nozzle sampling system. We describe a shrouded nozzle sampling system that was designed and built to sample 0.5–20 μm particles from a ventilation duct to an aerodynamic particle sizer (APS, Model 3320; TSI Inc., Shoreview, MN, USA) and we present experimental data characterizing system performance. Experimental measurements of the aspiration, transport, and total transmission efficiencies of the shrouded nozzle sampling system are presented and compared to previously published models. These data and models provide a basis for using an APS to measure real-time particle size distributions from ventilation ducts in buildings or in similar applications.

METHODS

Experimental Apparatus

Measurements of particle transmission and aspiration efficiencies through sampling nozzles reported here were made during the particle deposition experiments described in Sippola and Nazaroff (2004). Figure S1 in the online supplemental information (SI) presents a schematic diagram of the experimental duct system used in that work; a detailed description also is provided in the SI. Two sets of laboratory experiments were conducted, one in a steel duct system and the other in an internally insulated duct system. Experiments focused on measuring deposition rates of fluorescent monodisperse particles at two test duct sections shown in Figure S1. In the steel system, experiments were performed with 1, 3, 5, 9, and 16 μm diameter particles at nominal air speeds of 2.2, 5.3, and 9.0 m/s. In the internally insulated system, experiments with particle diameters of 1, 3, 5, 8, and 13 μm were conducted at air speeds of 2.2, 5.3, and 8.8 m/s. Transport and aspiration efficiencies for the shrouded nozzle system were measured only during experiments in the internally insulated system. Transport efficiencies for the isokinetic nozzles were measured in both the steel and internally insulated systems.

Monodisperse experimental particles tagged with a fluorescent tracer were injected into the duct system, and airborne particle concentrations were determined by fluorometric analysis of filters and the internal surfaces of nozzles and filter holders using wet chemistry. It is these concentration measurements, accomplished with four isokinetic nozzles sampling to filters and with shrouded nozzles sampling both to a filter and to an APS for each experiment, that form the foundation of the data presented here. Additional details of the experimental work are given in the SI, in Sippola (2002), and in Sippola and Nazaroff (2004).

Isokinetic Buttonhook Nozzles and Shrouded Nozzle

Two types of nozzles were used to sample the experimental aerosol in the ventilation duct: unshrouded isokinetic buttonhook nozzles and shrouded anisokinetic nozzles. Isokinetic buttonhook nozzles sampled to 47 mm nitrocellulose filters to measure airborne concentrations at four locations, two near test duct 1 and two near test duct 2, as seen in Figure S1. Figure S2 in the SI depicts an isokinetic buttonhook nozzle, and a detailed description of these nozzles is given in the SI. One shrouded nozzle delivered experimental particles to an APS for particle sizing in all experiments. For experiments in the insulated duct, a second shrouded nozzle sampled to a filter. The shrouded nozzles did not sample isokinetically; they sampled at a constant flow rate of 5.0 L/min—the APS sampling rate—regardless of the air speed in the duct.

Figure 1 depicts the shrouded nozzle, which comprises three parts: the shrouded inlet, the bend, and the outlet tube with mounting assembly. The inlet was mounted coaxially in the shroud. A schematic of a side-view section through the
FIG. 1. Photograph of a shrouded nozzle sampling system showing the shrouded inlet piece, the bend, and the outlet tube with the mounting assembly.

centerline of the shrouded inlet is shown in Figure 2, along with an end view. The bend and outlet tube had inner diameters of 17 mm, equal to the inner diameter of the shrouded inlet component at its outlet. The three parts were constructed to give a smooth internal fit at the joints. The outlet tube length was 13.5 cm and the centerline flow path through the 90° bend component was 9.5 cm. The flow path length through the shrouded nozzle from inlet to outlet was 28.9 cm, with 10 cm of horizontal length. In the end-view schematic, the three supports attaching the inlet to the shroud are visible. The waist of the shrouded nozzle, the narrowest open area between the nozzle and the shroud, can also be seen. Altering the waist area is the means by which the total airflow rate through the shroud, and therefore the degree of flow deceleration, is adjusted in shrouded nozzle design.

At typical duct air speeds, most air entering the shroud exits through the waist and a small fraction enters the nozzle inlet. Because of the flow constriction at the waist, air entering the shroud is decelerated. For a given sample flow rate and air speed, this deceleration allows for the use of a larger nozzle inlet than in the case of an unshrouded nozzle if isokinetic sampling is desired. The larger nozzle inlet leads to lesser particle losses at the inlet. The gradual expansion of the nozzle inner diameter immediately after the inlet allows for larger diameter transport lines, leading to less wall deposition and higher transport efficiencies. In addition to these benefits, the shroud reduces the magnitude of turbulent velocity fluctuations normal to the flow direction at the inlet and helps reduce sampling errors that would occur if the nozzle were not precisely aligned with the mean flow direction.

The shrouded nozzle described in Figure 2 is a scaled version of previous designs by McFarland et al. (1989), Ram et al. (1995), and Chandra and McFarland (1995). It was specifically designed to effectively deliver particles in the size range 0.5–20 μm from 1 to 20 m/s ventilation duct flows to an APS. An APS samples at a constant flow rate of 5.0 L/min through an inlet with a 19 mm outside diameter. With the sample flow rate and transport tube inner diameter fixed by the APS, the primary design decisions were the size of the nozzle inlet diameter and the shroud diameter. The modeling equations presented later in this article and in the SI were used to optimize total transmission through the shrouded nozzle sampling system. These design equations suggested high losses of large particles from inertial deposition at the inlet when \( d_{\text{inlet}} < 6 \text{ mm} \). The nozzle inlet also needed to be small enough to avoid extreme sub-isokinetic sampling, and \( d_{\text{inlet}} \) was set at 8 mm to meet this criterion. Aerodynamic testing and numerical flow simulations of previous shrouded nozzles showed air speeds through the waist area to be about 90% of the free stream air speed when the waist area is 30%–40% of the shroud cross-sectional area (McFarland et al. 1989; Gong et al. 1996). For the present design, the shroud diameter was selected so that the waist area would be about 40% of the shroud cross-sectional area, similar to the previous designs. Assuming the air speed through the waist area to be 90% of the free stream air speed, this waist area also maintained the ratio of the air speed in the shroud to the free stream air speed of about 0.4, as well as the ratio of \( d_{\text{inlet}} / d_{\text{shroud}} \sim 0.3 \), from the previous designs. The shroud length and the offset length were selected to maintain similar ratios of \( d_{\text{shroud}} / L_{\text{shroud}} \sim 0.27 \) and \( L_{\text{offset}} / L_{\text{shroud}} \sim 0.4 \) as in previous designs.

To sample isokinetically from 1 to 20 m/s duct air speeds at the APS sampling flow rate would require several isokinetic nozzle inlets with diameters in the range 1–7 mm. Because of wall losses, such small diameter nozzles and transport lines would be unlikely to reliably deliver particles larger than 3 μm to the APS. A shrouded anisokinetic sampling system with a larger nozzle inlet and a larger diameter transport line is better able to deliver 0.5–20 μm particles from the duct flow to the APS.

Models for Predicting Transport Efficiencies Through Nozzles

Predictions of particle transport efficiencies through the buttonhook nozzles and shrouded nozzle sampling system were
made using a combination of empirical equations presented by Brockman (2001). Deposition in transport lines by gravitational settling in nonvertical segments, Brownian diffusion, and inertial deposition in bends were taken into account. Brockman also presents equations for transport efficiencies through nozzle inlets when sampling velocities are not isokinetic. Turbulent diffusion was not included in the transport efficiency calculations because all transport line flows were laminar.

Equations used to calculate the transport efficiency through a short length just inside the nozzle inlet during nonisokinetic sampling ($\eta_{\text{inlet}}$) are presented in the SI, as are equations for estimating transport efficiencies owing to gravitational settling ($\eta_{g}$), Brownian diffusion ($\eta_{B}$), and deposition in bends ($\eta_{\text{bend}}$). Inlet deposition, gravitational settling, Brownian diffusion, and bend deposition were assumed to act independently so that the overall transport efficiency for a given particle size could be calculated as the product of efficiencies associated with each mechanism considered separately:

$$\eta_t = \eta_{\text{inlet}} \eta_{g} \eta_{B} \eta_{\text{bend}}. \quad [2]$$

**Models for Predicting Aspiration Efficiency at Sampling Inlets**

The empirical equation from Belyaev and Levin (1974) was used to predict aspiration efficiencies of the shrouded anisokinetic nozzle:

$$\eta_a = 1 + \left( \frac{u_o}{u_{\text{inlet}}} - 1 \right) \times \left[ 1 - \left[ 1 + St_{\text{inlet}} \left( 2 + \frac{0.617 u_{\text{inlet}}}{u_o} \right) \right]^{-1} \right] \quad [3]$$

for $0.005 \leq St_{\text{inlet}} \leq 10$ and $0.2 \leq \frac{u_o}{u_{\text{inlet}}} \leq 5$. For $St_{\text{inlet}} < 0.005$, where inertial effects are negligible, $\eta_a$ was assumed to be one.

With the shrouded nozzle, neither the shroud nor inlet nozzle sample isokinetically under most conditions and separate aspiration efficiencies can be defined for both. The aspiration efficiency of the shroud is

$$\eta_{a,\text{shroud}} = \frac{C_{\text{shroud}}}{C_{\text{bulk}}}, \quad [4]$$

where $C_{\text{shroud}}$ is the average concentration within the shroud immediately before the nozzle inlet. The aspiration efficiency of the inlet nozzle is defined by

$$\eta_{a,\text{inlet}} = \frac{C_{\text{inlet}}}{C_{\text{shroud,c}}}, \quad [5]$$

where $C_{\text{shroud,c}}$ is the concentration in the shroud immediately upstream of the nozzle inlet and near the shroud centerline.

The total aspiration efficiency for the shrouded nozzle is defined by

$$\eta_{a,\text{total}} = \frac{C_{\text{inlet}}}{C_{\text{bulk}}} \quad [6]$$

Predictions of $\eta_{a,\text{shroud}}$ and $\eta_{a,\text{inlet}}$ can be made using Equation (3). When predicting $\eta_{a,\text{shroud}}$, $u_o$ in this equation is the local speed of the airstream and $u_{\text{inlet}}$ is the average speed within the shroud upstream of the inlet. To predict $\eta_{a,\text{inlet}}$, $u_o$ in Equation (3) should be set equal to $u_{\text{shroud}}$ and $u_{\text{inlet}}$ is the average air speed at the nozzle inlet. It is not necessarily true that $\eta_{a,\text{total}}$ can be predicted by multiplying $\eta_{a,\text{shroud}}$ by $\eta_{a,\text{inlet}}$ because of the difference between $C_{\text{shroud}}$ and $C_{\text{shroud,c}}$. The shroud decelerates the flow; therefore, it samples sub-isokinetically leading to an enrichment of large particles within the shroud. As described by Gong et al. (1996), this enrichment is not uniform within the shroud; it is expected to be greater near the shroud walls where fluid streamlines diverge more than those near the centerline. Most of the flow with higher particle concentrations is expected to pass through the waist while the inlet nozzle samples the relatively unbiased aerosol at the shroud centerline. Values of $C_{\text{shroud}}$ are expected to be greater than those of $C_{\text{shroud,c}}$ because $C_{\text{shroud}}$ includes the flow regions near the shroud walls, where concentrations are higher.

Gong et al. (1996) developed a correlation for the ratio of $C_{\text{shroud,c}}$ to $C_{\text{shroud}}$ based on the results of numerical simulations of shrouded nozzles with Reynolds numbers in the range 8900–54,000 (based on the shroud diameter). They expressed this ratio, $F$, as

$$F = \frac{C_{\text{shroud,c}}}{C_{\text{shroud}}} = 1 - \left( \frac{u_o}{u_{\text{shroud}}} - 1 \right) \times \frac{0.861 St_{\text{shroud}}}{St_{\text{shroud}} \left( 2.34 + 0.939 \left( \frac{u_o}{u_{\text{shroud}}} - 1 \right) \right) + 1}. \quad [7]$$

$St_{\text{shroud}}$ is the Stokes number based on the shroud diameter and the local air speed

$$St_{\text{shroud}} = \frac{\tau蒲}{d_{\text{shroud}}}. \quad [8]$$

Gong et al. recommend predicting the total aspiration efficiency of a shrouded probe by means of this equation:

$$\eta_{a,\text{total}} = F \eta_{a,\text{shroud}} \eta_{a,\text{inlet}}, \quad [9]$$

where $\eta_{a,\text{shroud}}$ and $\eta_{a,\text{inlet}}$ can each be predicted using Equation (3).

In the modeling results presented here, the air speed through the shroud waist was assumed to be 90% of $u_o$ so that average speeds in the shroud were 36%–40% of $u_o$. Airflow measurements using hot-wire anemometers inside the shroud for free stream air speeds of 2.7 and 5.0 m/s are presented in the SI.
Average air speeds within the shroud were measured to be 46% and 41% of the free stream air speed for $u_o = 2.7$ and 5.0 m/s, respectively. Those measurements also suggest that the waist air speed was 96% of the free stream air speed for $u_o = 2.7$, and for $u_o = 5.0$ m/s that value was 87%.

Model predictions at the lowest speed showed maximum changes in total transmission efficiency of 3.6%, 0.6%, and 0.5% when the waist area air speed was equal to 50%, 70%, and 100% of $u_o$, respectively, suggesting that errors in this assumption would lead to acceptably small errors in predicting transmission efficiencies.

**Calculating Measured Transport and Aspiration Efficiencies**

The method of calculating transport and aspiration efficiencies from experimental measurements is presented in the SI.

**RESULTS**

**Transport Efficiencies in Isokinetic Buttonhook Nozzles**

Measured transport efficiencies for the isokinetic buttonhook nozzle are presented as a function of particle diameter for all three nominal air speeds in both the steel and insulated systems in Figure 3. Predicted transport efficiencies from the empirical model are also shown. For all model predictions, the particle density was assumed to be 1 g cm$^{-3}$; the density of experimental particles was in the range 0.9–1.3 g cm$^{-3}$. Because the nozzle inlets were located at the duct centerline, the air velocities at the inlets were higher than the average air speed. For similar nominal air speeds, centerline air velocities were slightly larger in the insulated system compared to the steel system. The model was applied using the slower inlet velocities in the steel system.

Each data point represents the average transport efficiency measured through the four nozzles in a given experiment. Error bars indicate the sample standard deviation and are only included when they are significantly larger than the data points. For two runs in the insulated system, one with 8 μm particles and an air speed of 5.3 m/s and one with 13 μm particles at 8.8 m/s, two data points are shown instead of a single point. For all experiments, two isokinetic buttonhook nozzles were clustered near test duct 1, and two more were clustered near test duct 2, but those two locations were in different sections of the duct system as shown in Figure S1. For each of these two runs, the transport efficiencies measured in two nozzles at test duct 1 agreed with each other, and those measured in nozzles near test duct 2 were in agreement, but there was poor agreement between data collected at the two different locations. For example, with 8 μm particles at 5.3 m/s, transport efficiencies through nozzles at test duct 1 were 0.245 and 0.218, while those at test duct 2 were 0.576 and 0.599. The two data points respectively represent the average transport efficiencies in the two nozzles near test duct 1 and test duct 2. The reason for this large discrepancy between the two locations is unclear.

**Transport and Aspiration Efficiencies in the Shrouded Nozzle**

Measured transport efficiencies through the shrouded nozzle sampling system versus particle size at the three nominal air speeds of 2.2, 5.3, and 8.8 m/s are shown in Figure 4. Here, as with all plots for the shrouded nozzle, each point represents a single measurement result. Transport efficiency predictions by the empirical model are also shown. Table S2 in the SI provides information on measured transmission through each component of the shrouded nozzle sampling system. In addition, the modeled transmission through each component and the absolute model-measurement error for each experiment are given in Table S2. Model-measurement errors are consistently less than 10%, as summarized in Table 1.

Measured total aspiration efficiencies of the shrouded nozzle versus particle diameter for the three nominal air speeds are shown in Figure 5. The model predictions were calculated using Equation (9) with individual aspiration efficiencies of the shroud and inlet nozzle calculated by Equation (3), with $F$ either calculated by Equation (7) or assumed to be unity. The measured total transmission efficiencies through the shrouded nozzle sampling system, $T_{total}$, are presented in Figure 6 along with model
predictions. The model (Equation (1)) includes predictions by the empirical transport efficiency model (Equation (2)) and by Equations (3) and (9) for total aspiration efficiencies, in this case assuming $F = 1$.

**DISCUSSION**

**Transport Efficiencies in the Isokinetic Nozzles and the Shrouded Nozzle**

In the top panel of Figure 3, measured transport efficiencies for the buttonhook nozzle at the lowest nominal air speed are nearly one for the smallest particles and decrease to near zero for the largest particles. At this lowest air speed, measured values are in reasonable agreement with the empirical model for all particle sizes. In the middle panel, at the intermediate air speed, measured transport efficiencies are again near one for the smallest particles; however, they are not close to zero for the larger particle sizes as is predicted by the model, and this same observation holds at the highest air speed.

A possible explanation for the trends revealed in the lower two frames in Figure 3 is that larger particles contacted the tube wall at the higher air speeds, but then the deposited fluorescent material was re-entrained into the airstream and transported to the filter. Such a hypothesized re-entrainment need not be a consequence only of simple resuspension or bounce, but may include contributions from complex liquid droplet interactions with walls as described by Yarin (2006). Potential contributing phenomena include partial rebound, splashing, and receding break-up, as well as coalescence of the liquid along the wall followed by release induced by shear, vibration, or some other mechanism. The experimental data and empirical model show good agreement at the lowest air speed, where re-entrainment is less likely, indicating that the model can yield reasonable predictions for some conditions. The model predicts that most of the deposition in the buttonhook nozzles occurs in the bend.

The combinations of particle sizes and air speeds exhibiting model-measurement disagreement here are the same conditions producing apparent re-entrainment of particles in the steel duct system as described in Sippola (2002) and Sippola and Nazaroff (2004). Specifically, blank runs in which clean air (i.e., with no added fluorescent experimental particles) was blown through the duct generated measurable airborne concentrations when the only potential source was particle-associated fluorescent

**TABLE 1**

| Air speed (m/s) | Inlet (-)       | Bend (-)        | Outlet tube (-) | Total (-)       |
|----------------|----------------|----------------|-----------------|----------------|
| 2.2            | 0.0001–0.0052  | 0.0002–0.0042  | 0.0003–0.0041  | 0.0007–0.0635  |
| 5.3            | 0.0018–0.0293  | 0.0010–0.0268  | 0.0008–0.0153  | 0.0039–0.0507  |
| 8.8            | 0.0025–0.0189  | 0.0014–1.0263  | 0.0018–0.0136  | 0.0005–0.0971  |

*Magnitude of absolute error = |modeled transmission–measured transmission|. 
FIG. 5. Total aspiration efficiencies for the shrouded nozzle versus particle diameter for the nominal air speeds of 2.2, 5.3, and 8.8 m/s. The model utilizes Equation (9) with individual aspiration efficiencies for the shroud and inlet nozzle calculated by Equation (3).

Material already deposited in the duct from a previous experiment. This unexpected result was repeatedly observed for \( d_p \geq 5 \mu m \) at air speeds of 5.3 and 9.0 m/s; the phenomenon did not occur for 1 or 3 \( \mu m \) particles, nor for any particles at an air speed of 2.2 m/s. It is for these same conditions (\( d_p \geq 5 \mu m \) and \( U \geq 5.3 m/s \)) where higher than predicted transport efficiencies through the isokinetic nozzles occurred. We find this evidence to be strongly suggestive that re-entrainment was occurring inside the buttonhook nozzles.

For the shrouded nozzle, agreement between the measured data and the transport efficiency model is reasonable at all air speeds (Figure 4). At \( U_{ave} = 2.2 m/s \), the average absolute error of the model was 2.5%, with a range of 0.1%–6.4%. Average absolute errors for \( U_{ave} = 5.3 m/s \) and \( U_{ave} = 8.8 m/s \) were
2.5% and 3.1%, respectively, with ranges of 0.4%–4.9% and 0%–9.7%.

Table S2 shows that absolute model-measurement errors for individual components of the shrouded nozzle sampling system are generally small, less than 1% for most cases. The largest errors were for the nozzle inlet, and the smallest were for the outlet tube. At the lowest air speed, the model underpredicts measured transport efficiencies mostly because it consistently overpredicts deposition at the inlet nozzle. The lowest air speed is the only case where the nozzle samples in a super-isokinetic fashion, meaning that Equation (S4) from the SI was used to calculate \( \eta_{\text{inlet}} \). At the higher air speeds, values of \( \eta_{\text{inlet}} \) as calculated by Equation (S1) from the SI, are in better agreement with measurements. The model predicts slightly higher transmission through the outlet tube than was measured for all cases. The very low deposition rates in the outlet tube meant that the experimental detection limits were a concern. Also, it is possible that deposition would be enhanced at the joints between components of the shrouded nozzle if the internal fit were not perfectly smooth. The single largest absolute error was in the bend for 8 \( \mu \)m particles at the highest air speed where modeled transmission was much higher than measured.

For the buttonhook isokinetic nozzles in this study, where average air speeds inside the transport lines were equal to the centerline duct velocities (up to 10.8 m/s), we have suggested that particle re-entrainment could have been the cause of the observed model-measurement discrepancy. In the shrouded nozzle sampling system, the air speed inside the transport lines was 0.37 m/s for all experiments. Re-entrainment at this low speed is much less likely to occur. High transport efficiencies through the isokinetic buttonhook nozzles for large particles at high air speeds may have been the result of particle re-entrainment. High transport efficiencies through the shrouded nozzle were probably a consequence of particles traveling through the transport lines without contacting the tube wall. Because particle re-entrainment is a poorly understood phenomenon, the high transport efficiencies through the shrouded nozzle sampling system are more reliably predictable than those in the isokinetic buttonhook nozzles.

**Aspiration Efficiencies in the Shrouded Nozzle**

As shown in Figure 5, measured total aspiration efficiencies are nearly one for all particle sizes at the lowest air speed. At the two higher air speeds, measured total aspiration efficiencies increase with particle size, and this effect was greatest at the highest air speed, 8.8 m/s. An increase in aspiration efficiency with particle size is expected because the air speed at the shrouded nozzle inlet is 1.7 m/s. As the free stream air speed increases above 5 m/s, the shrouded inlet samples at a rate that is more sub-isokinetic causing large particles to be oversampled.

The empirical aspiration efficiency model with \( F \) calculated by Equation (7) follows the same trends as the measured data, but it underpredicts the measured aspiration efficiencies. Setting \( F = 1 \) is equivalent to a simple cascade application of the aspiration efficiency equation to the shroud and nozzle inlet. That the model-measurement agreement is better with \( F = 1 \) than with \( F \) calculated by Equation (7) suggests that the factor \( F \) accounting for an unequal distribution of particles within the shroud is inappropriate for this application. A possible reason for this finding is that shroud Reynolds numbers in our experiments were in the range 2100–7500, lower and outside of the range for which Equation (7) was developed. As the shroud Reynolds number increases, \( C_{\text{shroud}} \) deviates more from \( C_{\text{isokin}} \), so that \( F \) decreases further from the value of one (Gong et al. 1996). Applying Equation (7) at lower shroud Reynolds numbers than for which it was developed could lead to underpredicting the value of \( F \).

For all air speeds and particle sizes studied, the measured total transmission efficiencies in the shrouded nozzle were appreciable, as seen in Figure 6. High total transmission efficiencies of large particles at high air speeds were a result of both high aspiration efficiencies and high transport efficiencies through the transport lines. High total transmission efficiencies are important for monitoring ambient particles in ventilation ducts with an APS. Ambient particles cannot be rinsed from nozzle interiors and quantified as was possible for the fluorescent experimental particles in these controlled experiments. The relatively low concentration of large particles in ventilation ducts makes it important that large particles are delivered with high transmission efficiency to the APS. Figure 6 suggests that good estimates of total transmission efficiency through the shrouded probe can be made for most particle sizes and air speeds of concern using the model presented here. For \( U_{\text{ave}} = 2.2 \) m/s, the average absolute error of the model was 5.7%, with a range of 1.8%–12%. Average absolute errors for \( U_{\text{ave}} = 5.3 \) m/s and \( U_{\text{ave}} = 8.8 \) m/s were 1.9% and 4.4%, respectively, with ranges of 0.9%–2.7% and 2.0%–9.4%.

The benefits of the shrouded nozzle sampling system are illustrated by comparing Figure 6 for the total transmission efficiency to that for the isokinetic buttonhook nozzles in Figure 3. A contribution to the performance differences derives from inefficiencies inherent in the shape of the buttonhook nozzles. Consequently, in weighing the relative merits of an isokinetic probe to a shrouded nozzle, we emphasize the general principle of improved and predictable particle transmission, rather than stressing the magnitude of the improvement. Similar, but smaller performance improvements would be expected when comparing the shrouded nozzle sampling system to an isokinetic nozzle possessing a smooth 90° bend.

An error analysis in which random errors are estimated by propagation of errors is provided in the SI for the measured data presented in Figures 4–6. This analysis suggests that random errors associated with measured values of \( \eta_i \) were in the range 0.004–0.010. Random errors in the aspiration efficiency and total transmission efficiency were respectively estimated to be in the ranges 0.013–0.054 and 0.014–0.042. Error estimates for each data point in Figures 4–6 are given in Table S3 of the SI.

This experimental and modeling work addresses the problem of sampling from ducts at constant low flow rates. However,
there are important limitations to the study presented here. Replicate experiments evaluating transmission efficiencies were not performed and so the statistical significance of the measurements cannot be evaluated beyond a standard propagation-of-error analysis. In addition, the flow field inside the shroud has not been studied in detail. Additional characterization could provide a more complete understanding of this shrouded nozzle sampling system that would make it more amenable to general use and further minimize sampling errors.

CONCLUSIONS

The presented transmission model and physical scaling process for shrouded nozzle design provide a framework for addressing the problem of sampling from a duct to a measurement device at a constant flow rate. We have built and characterized a shrouded nozzle sampling system that can be used to deliver an aerosol with particles in the range 1–13 μm (and probably beyond) from a ventilation duct to an APS that is sampling at a constant rate of 5.0 L/min. The concentration measured by the APS at the outlet of the shrouded nozzle sampling system could be corrected to approximate the actual particle size distribution in a ventilation duct using the models summarized here.

The anisokinetic shrouded nozzle sampling system has several advantages over isokinetic nozzles when sampling particles from duct flow at a constant low flow rate: higher total transmission efficiency for most particles, more predictable total transmission efficiency for most particles, and greater ease of use. The improved performance of the shrouded nozzle sampling system is greater for larger particles and higher air speeds, where higher total transmission rates result from both higher transport and higher aspiration efficiencies. Furthermore, the presented empirical models reliably predict the total transmission through the shrouded nozzle system. Experimental evidence indicates that transmission through the isokinetic buttonhook nozzles was more difficult to predict because high air speeds within the nozzles may lead to re-entrainment of material from deposited large liquid particles.

The empirical models produce good estimates of particle transmission through each component of the shrouded nozzle sampling system when compared to the experimental data, with model-measurement errors for each component usually less than 2%. Additional experimental investigation of the transmission efficiency and flow field within the shroud could improve confidence in applying the models and provide a more statistically robust characterization of this sampling system. The shrouded nozzle sampling system can be used to sample over a broad range of duct air speeds and the correlations presented here can be applied to relate measured particle size distributions to actual size distributions in the duct.

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