- SUPPLEMENTAL INFORMATION -

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

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METHODS

Experimental Apparatus

Measurements of particle transmission and aspiration efficiencies through sampling nozzles reported here were made during particle deposition experiments described in Sippola and Nazaroff (2004). Figure S1 is a diagram of the experimental duct system used in that work. Two sets of lab experiments were carried out, one with steel ducts and one with internally insulated ducts. The steel duct (Allied Mechanical HVAC; San Rafael, CA) consisted of several 1.5 m (5.0 ft) long sections with 15×15 cm (6.0×6.0 in) cross-section. The insulated ducts were steel with 20×20 cm (8.0×8.0 in) cross-sections and 2.5 cm (1.0 in) thick acoustic fiberglass insulation on all interior surfaces. Thus, the flow area in the insulated ducts was nominally the same as in the steel system. The insulation (ToughGard R, CertainTeed Corp., Valley Forge, PA) was fiberglass overlaid with a fibrous black composite surface on the airstream side.

For each experiment, monodisperse experimental particles tagged with a fluorescent tracer (ammonium fluorescein) were injected into the duct system. Particles were produced by means of a vibrating orifice aerosol generator (TSI Inc., Model 3450) and a Boltzmann charge distribution was imparted on the aerosol by passing it through a neutralizer (TSI Inc., Model 3054) with a Kr-85 radioactive source. Particles were generated from a liquid solution of isopropyl alcohol, oleic acid, and solid sodium fluorescein dissolved in 0.1 M aqueous ammonium hydroxide. Particles larger than $1 \mu\text{m}$ comprised a suspension of ammonium fluorescein in oleic acid; $1 \mu\text{m}$ particles were solid ammonium fluorescein.

FIG S1. Experimental duct apparatus in which the buttonhook isokinetic nozzles and shrouded nozzle sampled the fluorescent test aerosol. This schematic diagram is not drawn to scale.

Measurement of Deposited Particle Mass

Interior portions of nozzles and filter holders, along with filters, were extracted for fluorometric analysis after each experiment to determine the airborne particle concentrations in the duct and particle transport efficiencies through the nozzles. To determine the particle mass on filters, nozzle interiors and filter holders, each was rinsed with a known solution volume and the fluorescence of the resulting solution was measured with a fluorometer (Turner Designs, Model TD-700). Filters were rinsed by soaking and agitation in a known amount of solution. Deposited particles were recovered from filter holders and nozzles by repeatedly passing a small amount of solution from a measured quantity through the piece by means of small-volume disposable transfer pipettes. A minimum of three fluorescence measurements were performed for each piece and rinsing was repeated multiple times between each measurement. Further agitation and measurement was performed if the measured fluorescence had not stabilized by the third measurement.

Isokinetic Buttonhook Nozzles

Figure S2 depicts a buttonhook isokinetic nozzle and Teflon filter holder used in these experiments. Nozzles were inserted through a hole in the duct floor and secured with an external mounting assembly. Upon entering the inlet, aerosol flowing through this buttonhook nozzle encountered 2.9 cm of horizontal tube, a 126° bend with 4.8 cm flow path, a 2.1 cm length at an angle of 54° from the horizontal plane, a 36° bend, and finally a vertical length of 12.3 cm to the filter holder. Two sets of four buttonhook nozzles were used. Nozzles 1-4 (Model NS-6, Apex Instruments, Fuquay-Varina, NC), with internal diameters of 0.46 cm (0.180 in), were used in experiments with air speeds of 2.2 and 5.3 m/s, and nozzles 5-8 (Model NS-4, Apex Instruments, Fuquay-Varina, NC), with 0.30 cm (0.120 in) diameters, were used at air speeds of 8.8 and 9.0

m/s. Flow rates through buttonhook nozzles were maintained at isokinetic sampling rates so that expected aspiration efficiencies were always one. These flow rates were in the range 2-6 L/min, comparable in magnitude to the constant 5.0 L/min sampling rate for the shrouded nozzles.

Nozzles 5-8 were used at the highest mean duct air speed because not enough pumping capacity was available to achieve isokinetic sampling rates with nozzles 1-4.

Centerline air velocities at each sampling location were measured by means of a pitot tube to determine the proper pump flow rates for isokinetic sampling. Continuously adjustable pumps and a mass flow controller drew air through the nozzles at the isokinetic flow rate. Sampling flow rates were monitored using an electronic bubble flow meter (Giliblator, Gilian Instruments).

FIG S2. Photograph of a stainless steel isokinetic buttonhook nozzle with an external mounting assembly. The nozzle is attached to a 47 mm Teflon filter holder.

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.

Wall-deposition losses at inlets owing to sampling at nonisokinetic velocities were calculated by empirical equations. When sampling was sub-isokinetic, the transport efficiency through a short length just inside the nozzle inlet, η_{inlet} , was calculated by the following expression from Liu *et al.* (1989):

$$\eta_{inlet} = \frac{1 + \left(\frac{u_o}{u_{inlet}} - 1 \right) \left/ \left(1 + \frac{2.66}{St_{inlet}^{2/3}} \right) \right.}{1 + \left(\frac{u_o}{u_{inlet}} - 1 \right) \left/ \left(1 + \frac{0.418}{St_{inlet}} \right) \right.} \quad (S1)$$

$$\text{for } 0.01 \leq St_{inlet} \leq 100 \text{ and } 1 \leq \frac{u_o}{u_{inlet}} \leq 10$$

Here, St_{inlet} is the particle Stokes number at the inlet calculated with the local airstream velocity and the nozzle inlet diameter:

$$St_{inlet} = \frac{\tau_p u_o}{d_{inlet}} \quad (S2)$$

The particle relaxation time, τ_p , is calculated by

$$\tau_p = \frac{\rho_p d_p^2}{18\mu} \quad (S3)$$

where ρ_p is the particle density, d_p is the particle diameter and μ is the air viscosity.

Hangal and Willeke (1990) present an equation for η_{inlet} for super-isokinetic sampling:

$$\eta_{inlet} = \exp \left[-0.61 \left(\frac{St_{inlet} (u_{inlet} - u_o)}{u_o} \right)^{0.6} \right] \quad (S4)$$

$$\text{for } 0.02 \leq St_{inlet} \leq 4 \text{ and } 0.25 \leq \frac{u_o}{u_{inlet}} \leq 1$$

In our experiments, values of St_{inlet} for the shrouded nozzle were in the range $5 \times 10^{-4} - 0.26$. For $St_{inlet} < 0.02$, η_{inlet} was assumed to equal one. Values of u_{shroud}/u_{inlet} relevant for depositional losses immediately inside the shrouded nozzle were in the range $0.6 - 2.4$. Equations (S1) and (S4) are only applicable to nonisokinetic sampling and were therefore not applied to transport predictions in the isokinetic buttonhook nozzles.

Flow through the shrouded nozzle transport tubes was laminar, with $Re = 880$ for all experiments. For buttonhook nozzles, Reynolds numbers were in the ranges $750 - 1900$ (for 0.46 cm diameter nozzles) and $2100 - 2200$ (for 0.30 cm nozzles). The equation of Heyder and Gebhart (1977) for laminar flow in a circular tube was used to calculate the transport efficiency resulting from gravitational settling, η_g :

$$\eta_g = 1 - \frac{2}{\pi} \left[\kappa \sqrt{1 - \kappa^{2/3}} - \kappa^{1/3} \sqrt{1 - \kappa^{2/3}} + \arcsin(\kappa^{1/3}) \right] \quad (S5)$$

$$\kappa = \frac{3L_{t,nv} \tau_p g}{4d_t u_t} \cos(\beta_t) \quad (S6)$$

$$\text{for } v_g \sin(\beta_t) < u_t$$

where $L_{t,nv}$, is the length of a nonvertical segment of the tube, g is gravitational acceleration (9.81 m s^{-2}), d_t is the tube diameter, u_t is the air speed in the tube, and β_t is the angle of the axis of the tube segment measured from the horizontal plane.

The transport efficiency through the transport line owing to Brownian diffusion, η_B , was calculated by means of the analytical solution of Gormley and Kennedy (1949) for laminar flow through a straight tube.

$$\eta_B = 1 - 4.07h^{2/3} + 2.4h + 0.446h^{4/3} \quad \text{for } h < 0.0156 \quad (\text{S7})$$

$$\eta_B = 0.8191\exp(-7.314h) + 0.0975\exp(-44.6h) + 0.0325\exp(-114h) \quad (\text{S8})$$

for $h \geq 0.0156$

$$h = \frac{2D_B L_{t,total}}{u_t d_t^2} \quad (\text{S9})$$

Here, h is the diffusional deposition parameter, $L_{t,total}$ is the total tube length, and D_B is the particle Brownian diffusivity calculated by the Stokes-Einstein relationship with the Cunningham slip correction factor, as summarized in Friedlander (2000, Chapter 2). Equations (S7)-(S9) were applied to the entire length of the transport tubes, including bends. Deposition by Brownian diffusion in both the buttonhook isokinetic nozzles and the shrouded nozzle was calculated to be negligibly small for all particle sizes in the range 0.5-20 μm .

Brockman (2001) presented an equation for transport efficiency owing to deposition in a bend, η_{bend} , in laminar flow. The equation is a fit to experimental data collected by Pui *et al.* (1987) in bends where the ratio of the bend radius to tube radius, i.e. the bend ratio, was about 5.6:

$$\eta_{bend} = \left[1 + \left(\frac{St_t}{0.171} \right)^{2.64St_t + 2.242} \right]^{\frac{2}{\pi}\phi} \quad (S10)$$

Here, ϕ is the bend angle in radians and St_t is the particle Stokes number in the transport line calculated using the air velocity in the transport line and the tube diameter

$$St_t = \frac{\tau_p u_t}{d_t} \quad (S11)$$

The bend ratio in the shrouded nozzle transport tube was 2.0. For buttonhook nozzles, the bend ratios were 7.1 and 4.8. Equation (S10) was based on experimental data that did not distinguish among deposition mechanisms. Therefore, bend lengths were not included when applying equations (S5) and (S6) to estimate gravitational deposition because equation (S10) implicitly accounts for all deposition mechanisms in the bend. Equations (S5) and (S6) were only applied to straight nonvertical transport tubes.

To complete the transport efficiency model, 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 by

$$\eta_t = \eta_{inlet} \eta_g \eta_B \eta_{bend} \quad (S12)$$

Measurements of airflow within the shroud

Experiments to characterize the airflow within the shroud with hotwire anemometers (Sensor Electronics and Measurement Equipment, Model HT-400; Gliwice, Poland) were performed in a large wind tunnel that was different than the duct where the experiments with particles were conducted. The wind tunnel is 16 m long with a rectangular cross-section 2.2 m

wide and 1.5 m tall. Measurements were made at wind tunnel air speeds of 2.7 m/s, corresponding approximately to the lowest air speed for the duct experiments with particles, and 5.0 m/s, which was the maximum stable air speed achievable in the wind tunnel.

The shrouded nozzle sampling system was mounted near the centerline of the wind tunnel and air was drawn through the nozzle inlet at a rate of 5 L/min as measured by an electronic bubble flow meter. During the experiments in the wind tunnel, multiple air speed measurements were made along the shroud radius from the centerline to the shroud wall at a location 15 mm downstream of the shroud inlet (30 mm upstream of the inlet nozzle). The waist area gap was too small to allow accurate direct measurement of air speeds in that region with a hotwire anemometer. Air speeds through the waist area were determined by mass balance: the flow rate of air into the shroud must equal the sum of the flow rates through the inlet and the waist. The velocity profile inside the shroud and upstream of the inlet nozzle was determined from the series of anemometer measurements, and the total flow rate into the shroud was calculated from the measured velocity profile. The waist air speed was found by dividing the flow rate through the waist by the measured flow area at the waist.

The results of these measurements are provided in Table S1. At a free stream air speed of 2.7 m/s, the average air speed inside the shroud, $u_{ave,s}$, was 1.26 m/s so that the waist air speed, u_{waist} , was 2.6 m/s, about 96% of the free stream value. Similarly, at the 5 m/s free stream air speed, the waist air speed was 4.4 m/s, about 87% of the free stream value. For $u_o = 2.7$ and 5.0 m/s, the measured air speeds inside the shroud inlet were respectively 46% and 41% of the free stream value. Values of the airflow rates through the shroud, inlet, and waist are also presented in Table S1 as Q_{shroud} , Q_{inlet} , and Q_{waist} , respectively.

Table S1. Results of airflow measurements inside the shroud at free stream air speeds of 2.7 and 5.0 m/s.

u_o (m/s)	$u_{ave,s}$ (m/s)	Q_{shroud} (L min ⁻¹)	Q_{inlet} (L min ⁻¹)	Q_{waist} (L min ⁻¹)	u_{waist} (m/s)	u_{waist} / u_o (-)
2.7	1.26	46	5	41	2.6	0.96
5.0	2.04	75	5	70	4.4	0.87

Calculating Measured Transport and Aspiration Efficiencies

After each experiment, the particle mass deposited on filters, and on the interiors of nozzles and filter holders, was determined by wet chemistry and fluorometric measurement. From these measurements, airborne concentrations and transport efficiencies through both the isokinetic buttonhook nozzles and the shrouded nozzle could be calculated. The isokinetic nozzles had a known aspiration efficiency of one, so concentrations measured by these nozzles and filters were taken to be representative of actual concentrations in the duct.

The total aspiration efficiency of the shrouded nozzle is not expected to be equal to one, so the concentration measured by the shrouded nozzle reflects C_{inlet} , the concentration of particles entering the nozzle inlet, and not the actual airborne concentration in the duct at the shroud location, $C_{o,shroud}$. Isokinetic filter measurements – with aspiration efficiencies of one and reflecting actual airborne concentrations – made 4.1 m downstream of the shrouded nozzle were used to estimate $C_{o,shroud}$. Owing to particle deposition, the airborne concentration in the duct decreases as air travels downstream from the shrouded nozzle to the isokinetic nozzles. Values of $C_{o,shroud}$ were estimated from the isokinetic filter measurements using measured deposition velocities to the duct walls and following the same method described in Sippola and Nazaroff (2005). The change in particle concentration over the 4.1 m duct length was typically small, ranging from 0.1% for 1 μm particles to 14% for the largest particles; errors associated with this concentration projection were small compared to other sources. The experimentally measured

total aspiration efficiency of the shrouded nozzle could be calculated from values of C_{inlet} and $C_{o,shroud}$ by means of equation (6) from the main article.

Transport and Aspiration Efficiencies in the Shrouded Nozzle

Table S2 provides information on measured transmission through each component of the shrouded nozzle sampling system. The modeled transmission through each component and the absolute model-measurement error for each experiment are also given in Table S2.

Error Analysis

For each set of experimental conditions, multiple measurements of transport efficiencies through isokinetic nozzles were made, so that the uncertainty in those values could be estimated from the sample standard deviation of the measurements. For the shrouded nozzle sampling system, the transport, aspiration and total transmission efficiencies were measured only once for each experimental condition. Uncertainty estimate for these measured values were made by propagation of random errors as described by Bevin and Robinson (2003).

Estimates of measurement errors were based on instrument specifications and observed variability in equipment performance and experimental conditions. The fundamental quantities that were measured to determine the shrouded nozzle parameters include pump flow rates, liquid volumes, fluorescein concentrations, and particle sizes. The APS drew air at a nearly constant flow rate; to account for variations in the pump flow rate, the error was taken to be 0.05 L/min. Errors in liquid volume measurement during the wet-chemistry analysis were assumed equal to the specifications of the glassware used for measuring the volumes. Errors in fluorescein concentration measurements were taken to be 0.3 ng/mL, higher than the fluorometer resolution of 0.1 ng/mL. The higher error value was assumed to account for variations in the efficacy of

Table S2. Measured and modeled transmission through each component of the shrouded nozzle sampling system.

d_p (μm)	Air Speed (m/s)	Measured Transmission (-)				Modeled Transmission (-)				Model Error (-)			
		Inlet	Bend	Outlet	Total	Inlet	Bend	Outlet	Total	Inlet	Bend	Outlet	Total
1	2.2	0.9996	0.9994	0.9995	0.9985	0.9997	0.9996	0.9999	0.9992	0.0001	0.0002	0.0004	0.0007
1	5.3	0.9982	0.9985	0.9991	0.9959	1.0000	0.9996	0.9999	0.9998	0.0018	0.0010	0.0008	0.0039
1	8.8	0.9975	0.9981	0.9981	0.9938	1.0000	0.9996	0.9999	1.0000	0.0025	0.0014	0.0018	0.0062
3	2.2	0.9964	0.9963	0.9997	0.9923	0.9828	0.9966	1.0000	0.9794	-0.0136	0.0003	0.0003	-0.0130
3	5.3	0.9925	0.9945	0.9978	0.9848	0.9960	0.9968	1.0000	0.9928	0.0036	0.0022	0.0022	0.0079
3	8.8	0.9739	0.9906	0.9940	0.9590	0.9852	0.9969	1.0000	0.9821	0.0113	0.0062	0.0059	0.0231
5	2.2	0.9919	0.9851	0.9982	0.9754	0.9639	0.9894	1.0000	0.9536	-0.0281	0.0042	0.0018	-0.0218
5	5.3	0.9720	0.9868	0.9955	0.9549	0.9869	0.9923	1.0000	0.9793	0.0150	0.0055	0.0044	0.0244
5	8.8	0.9551	0.9827	0.9908	0.9298	0.9393	0.9905	1.0000	0.9303	-0.0158	0.0078	0.0092	0.0005
8	2.2	0.9677	0.9721	0.9963	0.9372	0.9335	0.9737	1.0000	0.9089	-0.0342	0.0016	0.0037	-0.0283
8	5.3	0.9403	0.9478	0.9909	0.8831	0.9510	0.9745	1.0000	0.9268	0.0107	0.0268	0.0091	0.0437
8	8.8	0.8663	0.8472	0.9916	0.7277	0.8473	0.9735	1.0000	0.8248	-0.0189	0.1263	0.0084	0.0971
13	2.2	0.9554	0.9339	0.9959	0.8885	0.8802	0.9373	1.0000	0.8250	-0.0752	0.0035	0.0041	-0.0635
13	5.3	0.8639	0.9260	0.9847	0.7878	0.8933	0.9386	1.0000	0.8384	0.0293	0.0126	0.0153	0.0507
13	8.8	0.7474	0.9118	0.9864	0.6722	0.7487	0.9400	1.0000	0.7038	0.0012	0.0282	0.0136	0.0316

rinsing, for imperfect mixing of the rinsing solution and for inconsistencies in the fluorometer calibration. The error in particle size measurement was taken to be the standard deviation of the particle size data from the APS. Errors varied among experiments because of variations in aerosol polydispersity, air speed, total deposited particle mass, wet-chemistry techniques and a variety of other factors. More details of this error analysis are provided in Appendix D of Sippola (2002).

Table S3 provides the results of this error analysis for the transport efficiency, the aspiration efficiency and the total transmission efficiency of the shrouded nozzle sampling system. Table S3 also shows the uncertainty in the particle size for each experiment, which was taken to be the standard deviation of the mass mean diameter measured by the APS. Errors in the shrouded nozzle variables η_t , η_a and T_{total} are in the range 0.004-0.054. When plotted on Figures 4-6 in the main manuscript, errors of this magnitude would be the size of the data points or smaller. Based on this error analysis, the shrouded nozzle performance data presented in Figures 4-6 are likely to represent the true values.

Table S3. Estimated random errors in measurements of particle behavior in the shrouded nozzle sampling system.

Nominal d_p (μm)	Air Speed (m/s)	Measured d_p (μm)	Error in d_p (μm)	Transport Efficiency (-)			Aspiration Efficiency (-)			Total Transmission Efficiency (-)		
				Value	Error	% Error	Value	Error	% Error	Value	Error	% Error
1	2.2	0.98	0.07	0.998	0.004	0.4	1.019	0.017	1.7	1.017	0.018	1.7
1	5.3	1.00	0.07	0.996	0.008	0.8	1.012	0.013	1.3	1.008	0.015	1.5
1	8.8	0.99	0.08	0.994	0.010	1.0	1.020	0.016	1.5	1.013	0.019	1.8
3	2.2	2.97	0.17	0.992	0.006	0.6	1.089	0.019	1.8	1.081	0.020	1.9
3	5.3	2.87	0.19	0.985	0.006	0.6	1.012	0.014	1.3	0.997	0.014	1.5
3	8.8	2.83	0.19	0.959	0.008	0.8	1.072	0.017	1.5	1.028	0.018	1.7
5	2.2	5.29	0.33	0.975	0.004	0.5	1.108	0.025	2.3	1.081	0.025	2.3
5	5.3	4.89	0.29	0.955	0.005	0.5	1.131	0.020	1.8	1.080	0.020	1.8
5	8.8	5.01	0.34	0.930	0.010	1.1	1.257	0.039	3.1	1.169	0.038	3.3
8	2.2	8.38	0.54	0.937	0.004	0.5	0.976	0.022	2.2	0.915	0.021	2.3
8	5.3	8.24	0.36	0.883	0.005	0.6	1.295	0.021	1.7	1.144	0.020	1.7
8	8.8	8.41	0.53	0.728	0.009	1.3	1.714	0.037	2.2	1.247	0.032	2.5
13	2.2	12.94	0.73	0.889	0.005	0.6	0.971	0.020	2.0	0.863	0.018	2.1
13	5.3	12.81	0.71	0.788	0.012	1.6	1.641	0.038	2.3	1.293	0.036	2.8
13	8.8	12.66	0.70	0.672	0.009	1.3	2.282	0.054	2.4	1.534	0.042	2.7

References

- Bevington, P.R., and Robinson, D.K. (2003). Error Analysis. In *Data Reduction and Error Analysis for the Physical Sciences*, McGraw-Hill, Inc., New York, New York.
- Brockman, J. E. (2001). Sampling and Transport of Aerosols. In Baron, P. A., and Willeke, K., editors, *Aerosol Measurement: Principles, Techniques, and Applications*, John Wiley & Sons, Inc., Hoboken, New Jersey.
- Friedlander, S.K. (2000). *Smoke, Dust, and Haze*, Oxford University Press, New York.
- Gormley, P.G., and Kennedy, M. (1949). Diffusion from a stream flowing through a cylindrical tube. *Proc. Royal Irish Acad.*, 52:163-169.
- Hangal, S., and Willeke, K. (1990). Overall efficiency of tubular inlets sampling at 0-90 degrees from horizontal aerosol flows. *Atmos. Environ.*, 24A:2379-2386.
- Heyder, J., and Gebhart, J. (1977). Gravitational deposition of particles from laminar aerosol flow through inclined circular tubes. *J. Aerosol Sci.*, 8:289-295.
- Liu, B. Y. H., Zhang, Z. Q., and Kuehn, T. H. (1989). A numerical study of inertial errors in anisokinetic sampling. *J. Aerosol Sci.*, 20:367-380.
- Pui, D. Y. H., Romay-Novas, F., and Liu, B. Y. H. (1987). Experimental study of particle deposition in bends of circular cross section. *Aerosol Sci. Technol.*, 7:301-315.
- Sippola, M. R. (2002). *Particle Deposition in Ventilation Ducts*, Ph. D. Dissertation, University of California, Berkeley, CA.
- Sippola, M. R., and Nazaroff, W. W. (2004). Experiments measuring particle deposition from fully developed turbulent flow in ventilation ducts. *Aerosol Sci. Technol.*, 38:914-925.
- Sippola, M. R., and Nazaroff, W. W. (2005). Particle deposition in ventilation ducts: Connectors, bends and developing turbulent flow. *Aerosol Sci. Technol.*, 39:139-150.