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Performance evaluation of six different aerosol samplers in a particulate matter generation chamber

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ABSTRACT

The present study was carried out with the aim of evaluating the performance of six different aerosol samplers in terms of mass concentration, particle size distribution, and mass fraction for the international size-sampling conventions. The international size-sampling criteria were defined as inhalable, thoracic, and respirable mass fractions with 50% cutoff at an aerodynamic equivalent diameter of 100 μm, 10 μm, and 4 μm, respectively. Two Andersen, four total suspended particulate (TSP), two RespiCon, four PM_{10}, two DustTrak, and two SidePak samplers were selected and tested to quantitatively estimate human exposure in a carefully controlled particulate matter (PM) test chamber. The overall results indicate that (1) Andersen samplers underestimate total suspended PM and overestimate thoracic and respirable PM due to particle bounce and carryover between stages, (2) TSP samplers provide total suspended PM as reference samplers, (3) TSP samplers quantified by a coulter counter multisizer provide no information below an equivalent spherical diameter of 2 μm and therefore underestimate respirable PM, (4) RespiCon samplers are free from particle bounce as inhalable samplers but underestimate total suspended PM, (5) PM_{10} samplers overestimate thoracic PM, and (6) DustTrak and SidePak samplers provide relative PM concentrations instead of absolute PM concentrations.

1. Introduction

Quantitative air sampling is used to gain knowledge of human exposure to particulate matter (PM; also known as particle pollution), a complex mixture of particles suspended in the air that vary in size, shape, and composition. The health effects of PM depend on their mass concentration and where they are deposited in the respiratory tract. For health-based airborne sampling, there is an international harmonization of particle size-selective sampling criteria defined by the American Conference of Governmental Industrial Hygienists (ACGIH, 1999), International Organization for Standardization (ISO, 1995), and the Comité Européen de Normalisation (CEN, 1993). These criteria were defined as inhalable, thoracic, and respirable with their 50% cutoff sizes at an aerodynamic equivalent diameter (AED) of 100 μm, 10 μm, and 4 μm, respectively. These PM size fractions deposit in a particular region of the respiratory tract: the inhalable fraction for PM entering the upper airways beyond the nose and mouth, the thoracic fraction for PM depositing beyond the larynx, and the respirable fraction for PM reaching the airspace deep in the lungs. The United States Environmental Protection Agency

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(USEPA) has promulgated the National Air Ambient Quality Standards (NAAQS) for PM_{10} and $PM_{2.5}$ defined as an AED less than or equal to a nominal 10 μm and 2.5 μm to protect human health and well-being (USEPA, 1997).

To estimate the potential hazard from PM, it is necessary to choose among many different aerosol sampling instruments which are commercially available to collect PM of varying size: total suspended particulates (TSPs, size ranging from about 0.002 μm to more than 100 μm), inhalable PM (AED $\leq$ 100 μm), thoracic PM (PM_{10}, AED $\leq$ 10 μm), respirable PM (PM_4, AED $\leq$ 4 μm), $PM_{2.5}$ (AED $\leq$ 2.5 μm), PM less than 0.1 μm, and condensable PM. In the present study, two Andersen, four TSP, two RespiCon, four PM_{10}, two DustTrak, and two SidePak samplers were used to estimate human exposure to PM. The goal of this study was to evaluate the performance of six different aerosol samplers in terms of mass concentration, particle size distribution (PSD), and mass fraction for the international size-sampling conventions in a carefully controlled PM test chamber. The performance of aerosol sampler is described by direct comparison of aerosol mass concentration measured with the sampler, relative to the concentrations which would have been obtained by using a reference sampler (CEN, 2002). However, this ideal reference sampler perfectly following the relevant sampling criteria does not actually exist, therefore knowledge of the PSD as a function of sampled PM permits the prediction of deposition in various regions of the respiratory tract. The following were the main purposes of the study: (1) to compare the total mass concentrations of TSP samplers, as reference samplers, with those of Andersens and RespiCons, (2) to find PSD characteristics of sampled PM in the chamber and to compare the PSDs measured from Andersens, TSP samplers, and bulk sample of PM, (3) to compare the mass fractions calculated from Andersens, TSP samplers quantified by a coulter counter multisizer (TSP/CCMs), and RespiCons for the international thoracic and respirable size-sampling conventions, (4) to compare the mass concentrations of PM_{10} samplers with those of Andersens, TSP/CCMs, and RespiCons, and (5) to compare the mass concentrations of DustTraks and SidePaks with the same cutoff size inlet.

2. Materials and methods

2.1. Description of aerosol samplers

In the present study, three types of aerodynamic size-selective aerosol samplers were used, including two Andersen cascade impactors (Model 20-800, Thermo Electron Co., Smyrna, GA, USA) with eight stages (Stages 0–7: AED >10.1, 6.5–10.1, 5.3–6.5, 3.7–5.3, 2.4–3.7, 1.2–2.4, 0.7–1.2, 0.5–0.7 μm) and a backup stage (AED < 0.5 μm) (Park, 2005), two RespiCon serial virtual impactors (Models 801132 and 801586; first stage cutoff AED of 4.0 μm and 2.5 μm, TSI, Inc., St. Paul, MN, USA) that simultaneously collects the international size-sampling fractions with three stages (stages 1 and 2: AED $\leq$ 4 μm & 4–10 μm for the 1st RespiCon and AED $\leq$ 2.5 μm & 2.5–10 μm for the 2nd RespiCon, respectively, stage 3: AED > 10 μm for both RespiCons), and four USEPA-approved PM_{10} samplers (Graseby-Andersen model SA246B, Thermo Electron Co., Smyrna, GA, USA). One type of volumetric particle size-selective analyzer, a CCM (Coulter Counter Multisizer III, Beckman Coulter Inc., Fullerton, CA, USA), was used with the samples collected from four TSP samplers (Wang et al., 2005; Wanjura et al., 2005). Two types of laser-light scattering particle samplers were used: two DustTrak (Model 8520, TSI Inc., Shoreview, MN, USA) and two SidePak (Model AM510, TSI Inc., Shoreview, MN, USA) real-time monitors.

2.2. Experimental setup

The chamber experiment was conducted at the Center for Agricultural Air Quality Engineering and Science (CAAQES) in Texas, USA. Fig. 1 shows the arrangement of six different aerosol samplers in a PM generation chamber. The polydisperse fly ash particles were used to represent industrial PM. The bulk density of fly ash was measured at 2.7 × (1 ± 3%) g cm^{-3} by a pycnometer (AccuPyc 1330, Micromeritics, Norcross, GA, USA). All 16 aerosol samplers were placed together at the height of human breeding zone as possible. The chamber was tested several times with TSP samplers prior to this study if the uniform mass concentration distributions were found in the PM exposure section. There was no significant difference between the measured mass concentrations from four TSP samplers as located in Fig. 1 (Wang et al., 2005). In the present study, the sampling performance of six different aerosol samplers was tested with the hypothesis that the PM in a chamber was distributed uniformly on the basis of a previous study.

The exposure section of the chamber was cubical with a length of 2.4 m on each side. The chamber was cleaned after each test before starting a new experiment with new fly ash. Andersens, DustTraks, and SidePaks were placed at a height of 115 cm; RespiCons at 150 cm; TSP and PM_{10} samplers at 160 cm above the chamber floor. The first and second tests were 1 h tests. The third test was intended to be 2 h, but because of trends toward filter overloading, TSP and PM_{10} samplers were stopped after 1 h. Planned 2-h tests were completed with Andersens, RespiCons, DustTraks, and SidePaks. DustTraks and SidePaks were oriented toward the opposite wind direction to avoid overloading PM onto the impaction plate quickly because the PM expected to deposit on the plate would bounce if the samplers become overloaded. PTFE Teflon filters (Cole–Parmer, Vernon Hills, IL, USA) with a 0.5 μm pore size were used for RespiCons, TSP, and PM_{10} samplers to ensure consistency throughout all tests (37 mm for RespiCons; 47 mm for TSP and PM_{10} samplers). Each filter and plate was desiccated before and after testing in a weighing room at 20 °C and 45% relative humidity for at least 24 h (USEPA, 1988; NIOSH, 1994). An analytical balance with precision ±10 μg (Model AG245, Mettler Toledo Inc., Hightstown, NJ, USA) was used to weigh each filter and plate three times before and after each experiment. The airflow rate for each Andersen was adjusted to 22.7 L min^{-1} and that for each TSP and PM_{10} sampler was adjusted to 16.7 L min^{-1} with the data loggers (HOBO H8 RH/Temp/2X External, Onset Computer Corp., Pocasset, MA, USA) at 12 s intervals. The required airflow for each Andersen, TSP, and PM_{10} sampler

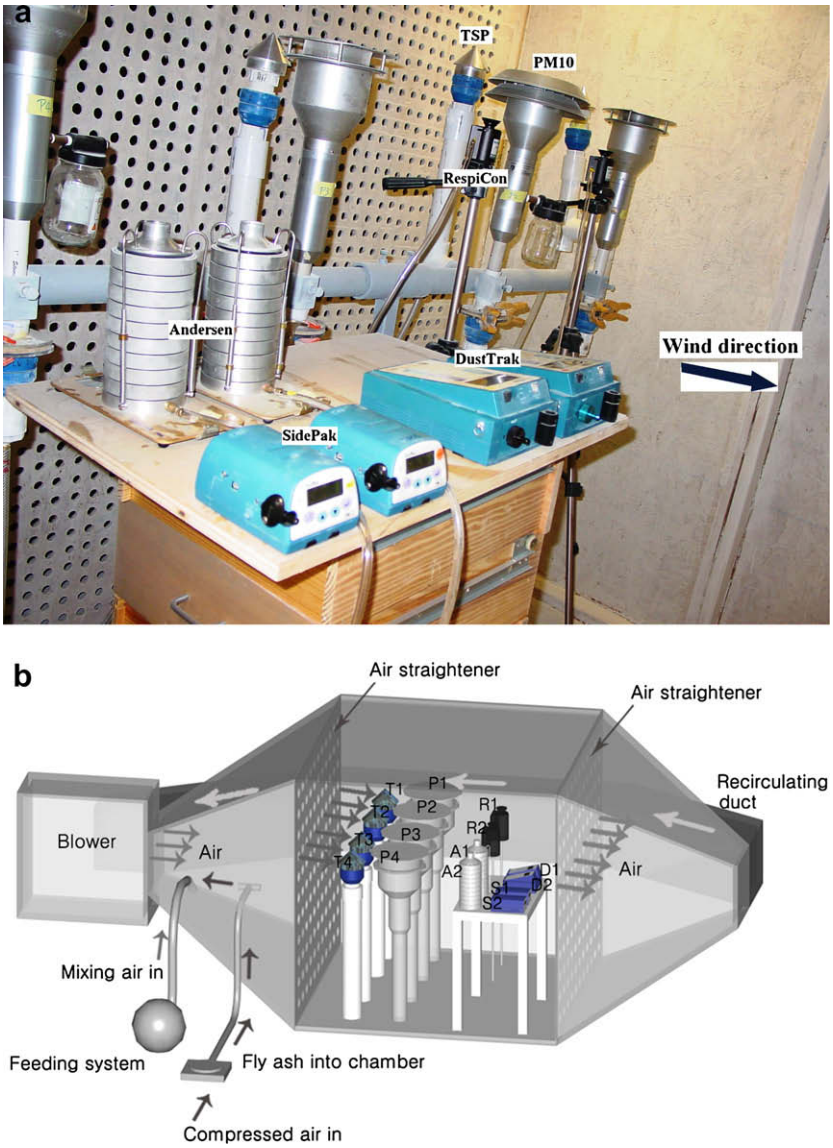


Fig. 1. (a) Pictures of six aerosol samplers and (b) experimental setup in a PM generation chamber. *Notes*: A1 and A2, Andersen samplers; T1–T4, TSP samplers; R1, RespiCon sampler with 4 μm and 10 μm cutoff fractions; R2, RespiCon sampler with 2.5 μm and 10 μm cutoff fractions; P1–P4, PM_{10} samplers; D1, DustTrak monitor used a 10 μm inlet; D2, DustTrak monitor used a 2.5 μm inlet; S1, SidePak monitor used a 2.5 μm inlet; S2, SidePak monitor used a 1 μm inlet.

was controlled with a needle valve (Model A-68831-00, Cole–Parmer, Vernon Hills, IL), a diaphragm pump (Item 4z792, Thomas, Sheboygan, WI), and a flow-restricting orifice (made in-house; Wang et al., 2005). The airflow rate for each RespiCon was adjusted to 3.1 L min^{-1} using a diaphragm pump (Gast DOA-104-AA, Taylor Scientific, St. Louis, MO, USA) and was calibrated using a flowmeter with an accuracy of ±3% (Visi-Float, Dwyer instruments, Michigan City, IN, USA). The airflow rate for each DustTrak and SidePak was adjusted to 1.7 L min^{-1} and was zeroed with a zero filter before each experiment. Data of real-time monitor were logged into the memory at 1 s intervals during each test. One DustTrak was set for a 10 μm cutoff and the other for a 2.5 μm cutoff. One SidePak was set for a 2.5 μm cutoff and the other for a 1 μm cutoff. Andersen impaction plates were cleaned and coated with vacuum silicone grease to minimize bounce phenomena (May, 1945; Swanson et al., 1996; Mitchell and Nagel, 2003). The impactor plates of DustTraks and SidePaks were also cleaned and smeared with a thin layer of grease to minimize particle bounce.

2.3. Analytical procedure for PSD and mass fractions

The experimental 256 PSD data from each TSP/CCM was entered into the ReliaSoft Weibull^{++} program (ReliaSoft Corporation, Tucson, AZ, USA) to find the best fit parametric distribution from the sampled fly ash. The software ranked for the best distribution of lognormal, normal, exponential 1-parameter, exponential 2-parameter, Weibull 2-parameter,

and Weibull 3-parameter distributions. The results show that the lognormal distribution ranked first in 9 of 11 data sets, and it ranked second and third when the Weibull 2-parameter distribution was ranked first. The PSD data from the bulk sample also show that the lognormal distribution ranked first. The significance of a lognormal distribution is that the PSD can be described in terms of two parameters, the geometric mean (GM) and the geometric standard deviation (GSD). In the present study, the mass median aerodynamic diameter (MMAD) represents the GM and is the AED having cumulative collection efficiency of 50%. The GSD is calculated by $\sqrt{d_{84.1}/d_{15.9}}$ where $d_{84.1}$ and $d_{15.9}$ are the AEDs having cumulative collection efficiencies of 84.1% and 15.9%, respectively (Hinds, 1999). The PSDs were obtained from Andersens, TSP/CCMs, and the bulk sample of fly ash by a CCM.

In Andersens, the PSDs were estimated from the eight cumulative mass fractions less than the cutoff AED of each stage (stages 0–7; AED 10.1, 6.5, 5.3, 3.7, 2.4, 1.2, 0.7, and 0.5 in μm). The mass fractions of thoracic and respirable PM were determined by the cumulative mass fractions of AED $<$ 10.1 μm and $<$ 3.7 μm which were close to respirable (AED $\leq$ 4 μm) and thoracic (AED $\leq$ 10 μm) conventions. A log–probit analysis (Rock, 1995) was conducted to find the PSD characteristics, an MMAD and GSD, as follows.

$$z = \frac{x-\mu}{\sigma} \approx \frac{\ln(\mathrm{AED}) - \ln(\mathrm{MMAD})}{\ln(\mathrm{GSD})}$$

$$\ln(\mathrm{AED}) \approx \ln(\mathrm{GSD}) \times z + \ln(\mathrm{MMAD}) \quad (1)$$

where z is the standard normal random variable calculated using NORMINV(mass fraction,0,1) in a Microsoft excel program, x is the normal random variable (cutoff AED), μ is the true population mean, and σ is the true population standard deviation.

In TSP/CCMs, the result of analysis was a particle volume fraction as a function of an equivalent spherical diameter (ESD) which had the same volume as an irregular particle. The CCM was operated with its 100 μm aperture installed to obtain the PSDs from TSP samplers. The CCM counts the particle size range in terms of ESD ranging from 2% to 60% of an aperture diameter (the number of data from each TSP/CCM = 256) that corresponds to AEDs ranging from 3.3 μm to 98.6 μm by multiplying ESDs of a TSP/CCM by the density of fly ash and a shape factor as follows (Hinds, 1999).

$$\mathrm{AED} = \mathrm{ESD}\left[\frac{\rho_p}{\rho_0 \times \chi}\right]^{1/2} \quad (2)$$

where ρ_p is the particle density, ρ_0 is the unit density (1 g cm^{-3}), and χ is the shape factor.

The cumulative collection efficiency for the truncated AED $<$ 3.3 μm was estimated using a lognormal function with the MMAD and GSD of each TSP/CCM. The estimated cumulative collection efficiency for AED $<$ 3.3 μm was combined with the original TSP/CCM data, then best MMAD and GSD were estimated. The mass fractions for the thoracic and respirable PM of a TSP/CCM were obtained from the calculated mass fractions of AEDs 10 μm and 4 μm, respectively. The best PSDs for the bulk sample of fly ash and fly ash sampled from Andersens and TSP samplers were estimated using raw data through a log–probit analysis and a linear regression analysis at the 95% prediction level with a Mathematica (Wolfram Research Inc., Champaign, IL, USA) program (Park, 2005).

2.4. Propagation of uncertainty

The concept of uncertainty propagation (Taylor, 1997) was applied to air sampling technologies to obtain a reliable estimate from inevitable errors in measurements such as a filter weighing and a volume flow rate. The uncertainty of a mass concentration U_C was calculated with the filter or plate of each Andersen, TSP, RespiCon, PM_{10} sampler as follows:

$$C = \frac{M}{Q \times T} \quad (3)$$

$$\frac{U_C}{\overline{C}} = \sqrt{\left(\frac{\mathrm{SD}_M}{\overline{M}}\right)^2 + \left(\frac{\mathrm{SD}_Q}{\overline{Q}}\right)^2 + \left(\frac{\mathrm{SD}_T}{\overline{T}}\right)^2} \quad (4)$$

where C is the mass concentration, M is the mass of particles on the impaction plate (Andersens) and the filter (TSP, RespiCon, and PM_{10} samplers), Q is the flow rate, T is the time, "–" indicates the average of each parameter, and SD is the sample standard deviation.

A weighted average and its uncertainty were calculated to provide best estimate from the number of each type of sampler as follows because the simple average $(C_1 + C_2)/2$ of two mass concentrations, C_1 and C_2, was unsuitable when $U_{C_1} \neq U_{C_2}$:

$$x_{\mathrm{wav}} = \frac{\sum \frac{1}{U_{x_i}^2} x_i}{\sum \frac{1}{U_{x_i}^2}} \quad (5)$$

$$U_{x_{\mathrm{wav}}} = \frac{1}{\sqrt{\sum \frac{1}{U_{x_i}^2}}} \quad (6)$$

where x_{wav} is the weighted average of individual measurements $x_1, \ldots, x_n$ (mass concentration, mass fraction, MMAD, and GSD) for each type of sampler.

Uncertainty in sums and a power was also applied to provide a range of possible true values for the cumulative parameters (mass concentrations and mass fractions) from the stages of impactors (Andersens and RespiCons) and from the AED conversion in TSP/CCM, respectively.

3. Results and discussion

3.1. Mass concentration

The mass concentrations measured from aerosol samplers are shown in Table 1. Inspection of mass concentrations shows that Andersens and RespiCons underestimated total suspended mass concentration when compared with TSP samplers. The normalizing factors

Table 1
Mass concentration measured from aerosol samplers.

Sampler		Andersen		TSP				RespiCon	
$\overline{C}$ (U_C)[a] [mg m^{-3}]	Test 1	29.2 (0.3)	29.5 (0.3)	33.6 (1.2)	34.5 (0.9)	31.6 (0.9)	34.7 (0.9)	20.8[b] (0.9)	**
	Test 2	21.4 (0.3)	21.5 (0.3)	24.0 (1.0)	24.5 (0.7)	25.6 (0.9)	25.2 (0.8)	**	**
	Test 3	23.0 (0.3)	23.9 (0.3)	25.0 (1.2)	25.7 (1.8)	30.0 (1.4)	30.0 (1.4)	16.3[b] (0.5)	31.9[c] (1.0)
	All tests	24.2 (0.1)		28.5 (0.3)				19.9 (0.4)	

Sampler		PM_{10}				DustTrak		SidePak	
Inlet cutoff size [μm]		10				10	2.5	2.5	1
$\overline{C}$ (U_C) [mg m^{-3}]	Test 1	26.1 (0.4)	33.7 (0.7)	25.9 (1.0)	24.3 (3.1)	11.9 (4.6)	7.2 (2.8)	13.0 (4.6)	14.3 (5.3)
	Test 2	16.9 (0.5)	23.9 (0.7)	18.7 (0.7)	17.7 (2.3)	9.4 (3.7)	4.7 (1.9)	9.4 (3.6)	7.7 (3.2)
	Test 3	21.8 (0.8)	24.4 (1.1)	21.2 (1.0)	20.4 (2.7)	11.4 (4.4)	5.8 (2.5)	11.4 (4.3)	11.3 (4.6)
	All tests	23.4 (0.2)				10.7 (2.4)	5.5 (1.3)	10.9 (2.4)	10.0 (2.4)

**No measurement due to a pump problem.
[a] $\overline{C}$, average mass concentration; U_C, uncertainty of an average mass concentration.
[b] RespiCon sampler with 4 μm and 10 μm cutoff fractions.
[c] RespiCon sampler with 2.5 μm and 10 μm cutoff fractions.

(1.18, a range of 1.16–1.20 for Andersens; 1.43, a range of 1.39–1.48 for RespiCons) were obtained as follows:

$$\text{Normalizing factor} = \frac{\text{Reference sampler}}{\text{Normalizing sampler}} \quad (7)$$

The TSP sampler was used as a reference sampler for the total suspended PM mass concentration because it, alone among these samplers, was designed to measure total PM. In the present study, Andersen samplers were used to measure the PSD as well as total mass concentration (Dzubay et al., 1976; Kent et al., 2001; Hitzenberger and Tohno, 2001). The normalizing factor for Andersens shows that there is an average 18% loss of total suspended PM mass. This result was consistent with the observation after each experiment when Andersens were cleaned. Many particles were found on the wall and in the holes of the orifice plates for each stage of the Andersens (May, 1945; Cushing et al., 1979; Vaughan, 1989; Horton et al., 1992). The normalizing factor for RespiCons suggests that there is an average 43% loss of total suspended PM mass. The result was also consistent with the observation that many particles were found in the center hole when RespiCon samplers were cleaned.

In Table 1, the DustTrak and SidePak with the same 2.5 μm inlets have different mass concentration. The indicated concentration measurement range of a DustTrak was from 0.002 mg m^{-3} to 100 mg m^{-3} (150 mg m^{-3}; an experimental maximum range) while that of a SidePak was from 0.001 mg m^{-3} to 20 mg m^{-3}. When data were analyzed from SidePaks, there were "invalid" signs in Tests 1 and 3 instead of the 1 s interval value of concentration for 6% and 7% of the intervals when using a 2.5 μm inlet and for 10% and 11% of the intervals when using a 1 μm inlet, respectively. There were no "invalid" signs from DustTraks. These signs were recorded when the values of SidePaks were above the maximum range (20 mg m^{-3}). It

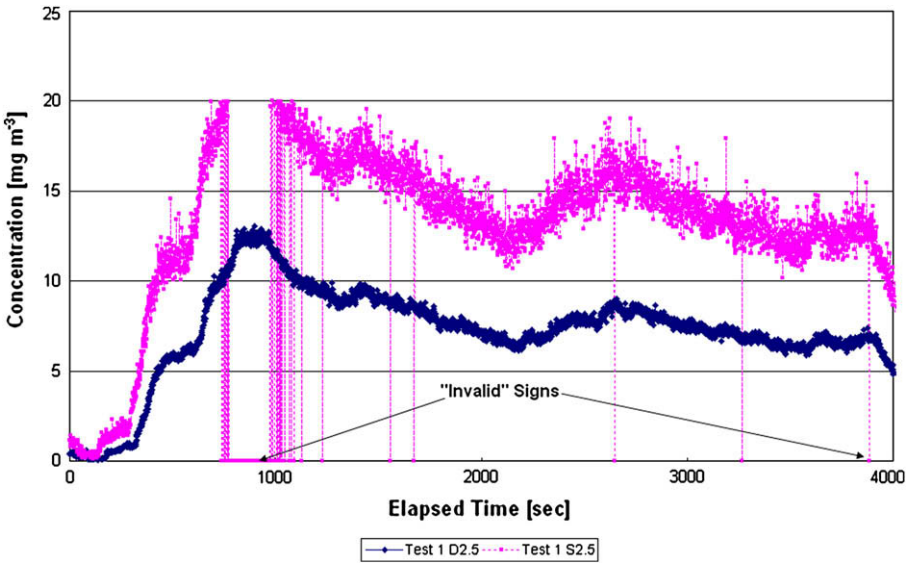


Fig. 2. Relative PM mass concentration measurements by real-time monitors.

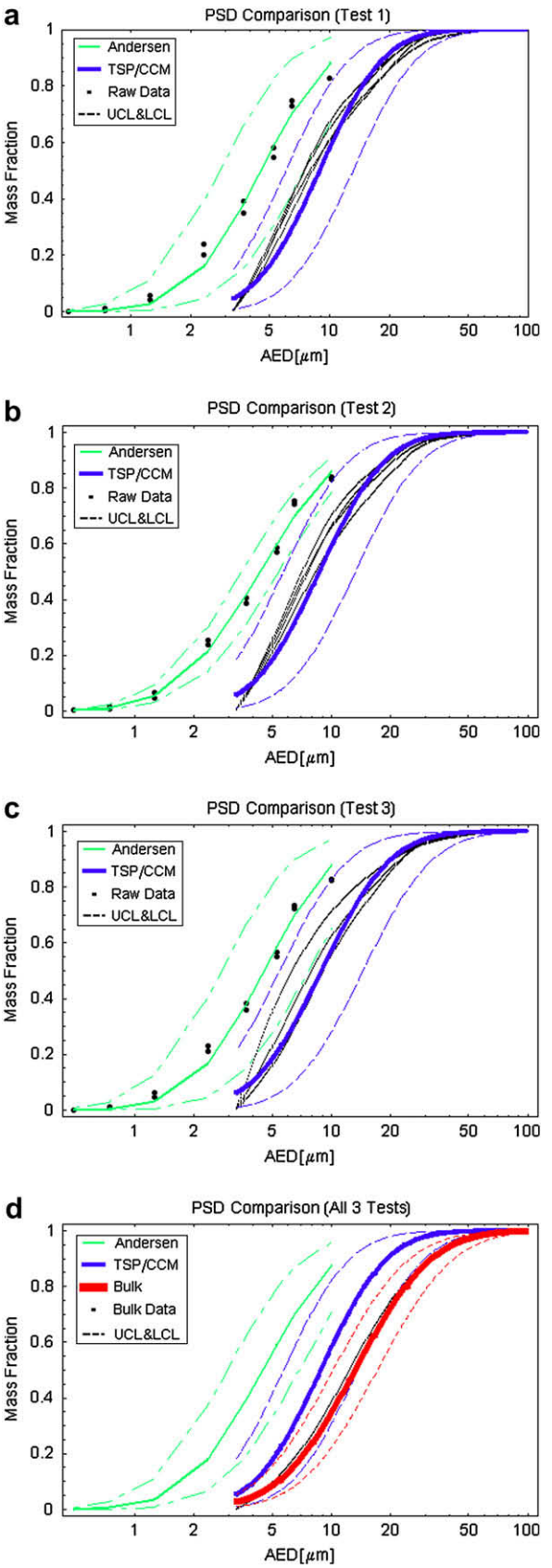


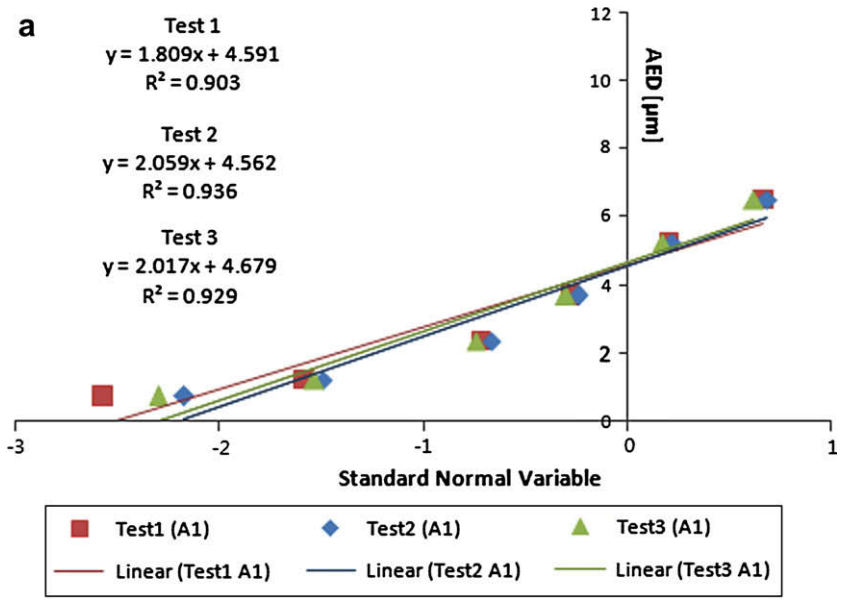
Fig. 3. PSDs of Andersens, TSP/CCMs, and the bulk sample of fly ash in the (a) test 1, (b) test 2, (c) test 3, and (d) all 3 tests. *Notes*: UCL, upper confidence limit; LCL, lower confidence limit.

was confirmed that most of these signs occurred during intervals when higher concentration was reported by the DustTrak. Fig. 2 shows that the mass concentrations measured by a DustTrak and a SidePak have the same overall shape but have different calibration factors when both samplers were used with the same size inlet of 2.5 μm in the first test. This means that these instruments are useful for measuring relative PM concentrations over time, but not for absolute PM concentration measurements.

3.2. Particle size distribution

All the PSDs with raw data were shown on the graph to compare the PSDs of Andersens, TSP/CCMs, and the bulk sample of fly ash. In Fig. 3, the best PSDs with thick lines were estimated from each 8 cumulative mass fraction data set of two Andersens, each 256 cumulative mass fraction data set of 4 TSP/CCMs, and the data set of 256 mass fraction of bulk sample of fly ash by a CCM at the 95% confidence level, respectively. The PSD of bulk fly ash injected into the chamber appears to have a higher mass fraction of all sizes than were evident in the PSDs obtained by Andersens and TSP/CCMs. The reasons for this difference include: particle losses on; the walls, the holes in the air straighteners, the fan blades and feeding nozzle which injects the fly ash. Fig. 3 also shows that there is a difference between the PSD curves of Andersens and those of TSP/CCMs. This difference is consistent with the bounce phenomena in Andersens. Mass transport by particle bounce causes the PSD slope to be flattened. The Andersens tended to show more mass in small AED fractions, and to show less mass in large AED fractions.

In Fig. 4, the log–probit plot was constructed to find the best estimates of the MMAD and GSD from Andersens by plotting the AEDs versus the probit of collection efficiencies. The mass fractions at stages 0 and 7 (cumulative mass fraction less than the cutoff AED of each stage) were neglected to obtain a best log–probit curve because both deviated from the expected straight line. This deviation is explained by the inlet design and the PM in very small quantities at stage 7 (AED $<$ 0.5 μm). The round inlet of an Andersen may undersample the PM with sufficient inertia at the operating air velocity in the chamber. In some cases at stage 7, the weighing uncertainty was above 1 due to a small quantity of mass (net mass in the fifth decimal place) weighed by a five-decimal-place precision balance. Table 2 shows the PSD characteristics of sampled PM from Andersens and TSP/CCMs. The best MMAD and GSD were estimated at (4.67 $\pm$ 0.02) μm and 1.93 $\pm$ 0.01 from all Andersens. Those of TSP/CCMs were estimated at (6.52 $\pm$ 0.08) μm and 1.86 $\pm$ 0.02. When the MMAD and GSD of Andersens were compared with those of TSP/CCMs, the wall losses of PM and bounce phenomena of Andersens were quantified by the relatively small MMADs and large GSDs of Andersens, respectively. The



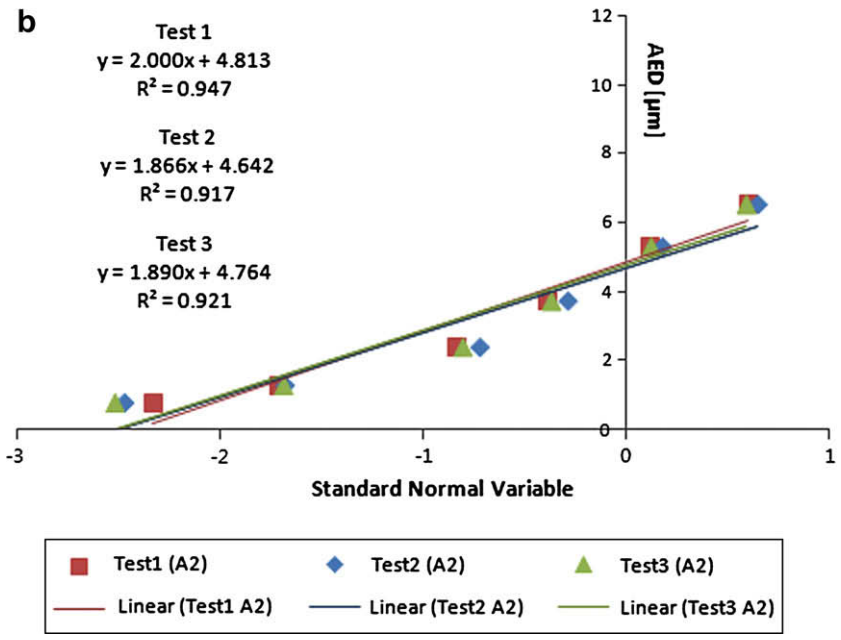


Fig. 4. Estimated MMAD and GSD from the (a) first Andersen and (b) second Andersen.

material characteristics of bulk sample of fly were estimated at 11.77 μm (MMAD) and 2.06 (GSD) by a CCM. The smaller MMADs and GSDs of aerosol samplers than that of the bulk sample of fly ash explain the PM losses, more AED $\leq$ 11.77 μm than AED $>$ 11.77 μm, on the walls and in the feeding system of a chamber.

3.3. Mass fraction

The mass fractions for thoracic and respirable PM were calculated to estimate the cumulative collection efficiency from Andersens, TSP/CCMs, and RespiCons for the international size-sampling conventions. Fig. 5 shows that Andersens have 97% and 85% more respirable PM mass fraction than that in TSP/CCMs and RespiCons, as well as 14% and 17% more thoracic PM mass fraction than that in TSP/CCMs and RespiCons, respectively. These results show that Andersens had particle bounce and carryover between stages even if the stainless steel impaction plates were coated with vacuum silicone grease (Turner and Hering, 1987; Dunbar et al., 2005). The larger respirable mass fraction, as well as the flatten PSD, of Andersens explains

Table 2
Estimated PSD parameters from Andersen and TSP/CCM samplers.

Sampler		Andersen		TSP/CCM			
		A1	A2	T1	T2	T3	T4
MMAD (U_{MMAD})[a] [μm]	Test 1	4.59 (0.05)	4.81 (0.05)	6.39 (0.27)	7.10 (0.24)	6.56 (0.24)	6.65 (0.22)
	Test 2	4.56 (0.05)	4.64 (0.06)	6.14 (0.28)	6.65 (0.24)	6.30 (0.25)	7.10 (0.27)
	Test 3	4.68 (0.05)	4.76 (0.06)	4.90 (0.25)	6.65 (0.48)	**	8.33 (0.42)
	All tests	4.67 (0.02)		6.52 (0.08)			
GSD (U_{GSD})[b]	Test 1	1.81 (0.02)	2.00 (0.02)	1.84 (0.08)	1.92 (0.06)	1.79 (0.07)	1.96 (0.06)
	Test 2	2.06 (0.02)	1.87 (0.02)	1.74 (0.08)	1.81 (0.07)	1.84 (0.07)	1.97 (0.07)
	Test 3	2.02 (0.02)	1.89 (0.02)	1.69 (0.09)	1.92 (0.14)	**	1.96 (0.10)
	All tests	1.93 (0.01)		1.86 (0.02)			

**The filter was used to get images from a microscope.
[a] MMAD, mass median aerodynamic diameter; U_{MMAD}, uncertainty of an average mass median aerodynamic diameter.
[b] GSD, geometric standard deviation; U_{GSD}, uncertainty of a geometric standard deviation.

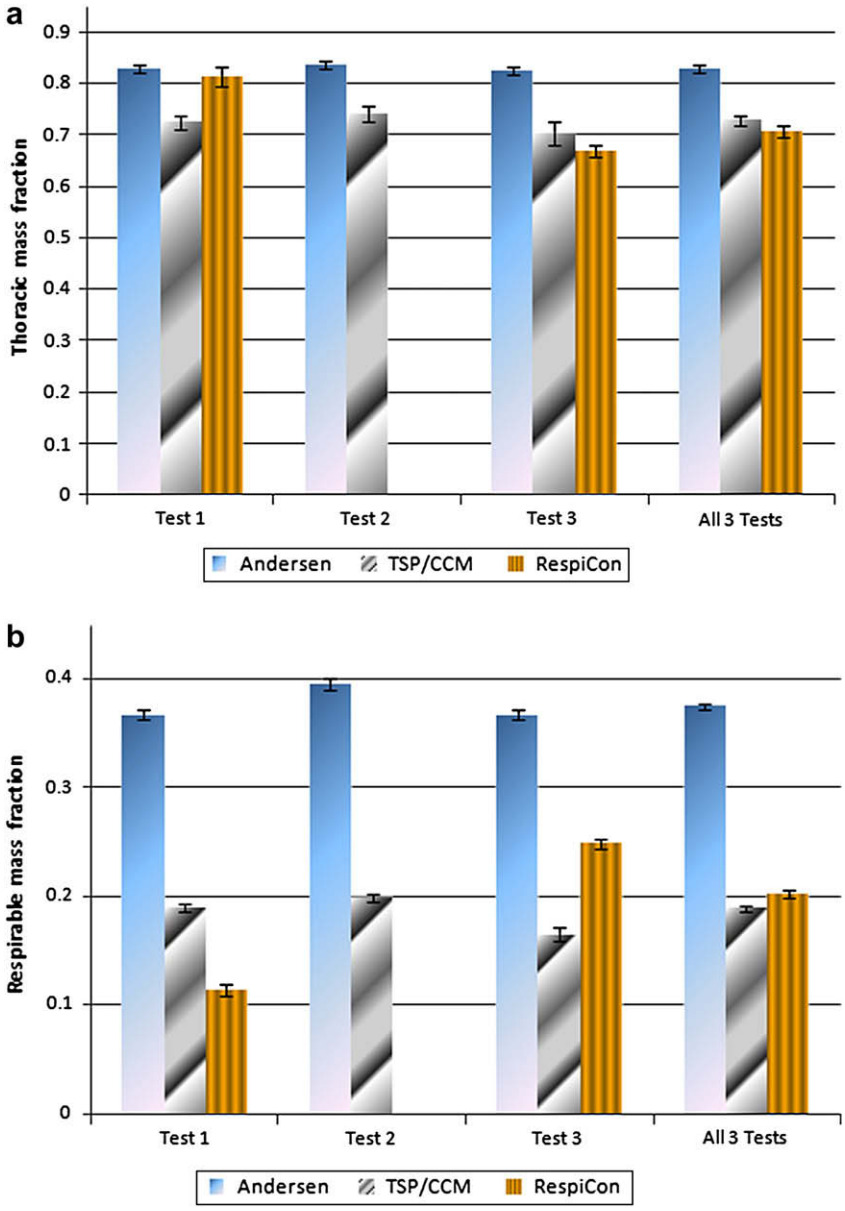


Fig. 5. Mass fractions of (a) thoracic PM and (b) respirable PM from Andersen, TSP/CCM, and RespiCon samplers.

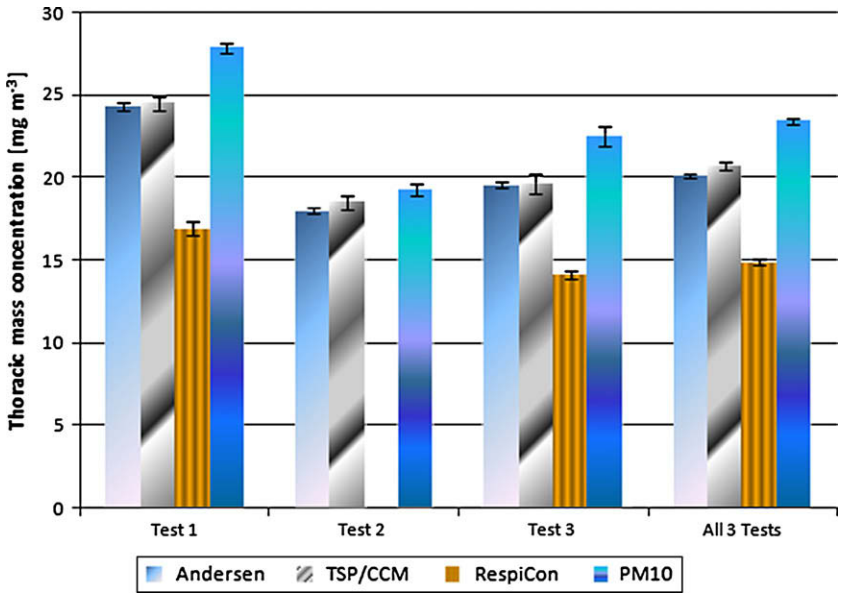


Fig. 6. Mass concentrations of PM_{10} samplers versus thoracic mass concentrations estimated from Andersen, TSP/CCM, and RespiCon samplers.

the particle bounce by the particle–particle interactions on the new made particle layer when an impaction stage is overloaded.

The mass concentrations of PM_{10} samplers were compared with the thoracic mass concentrations of Andersens, TSP/CCMs, and RespiCons. The thoracic PM mass concentration of each Andersen and TSP/CCM was estimated by multiplying a thoracic mass fraction by a total mass concentration for each sampler. The error bars in Figs. 5 and 6 represent uncertainty of the weighted average from each type of sampler. Fig. 6 shows that PM_{10} samplers had more PM mass concentration than Andersens, TSP/CCMs, and RespiCons. Careful comparison of the USEPA ideal PM_{10} curve, cutoff size of 10 μm ± 0.5 μm (USEPA, 2001) having a slope of 1.5 ± 0.1 (Wang et al., 2005) with the international thoracic curve (equation source from ACGIH, 1999) reveals that the USEPA specification has a steeper slope. This means that the USEPA sampler will collect a larger number of small PM slightly below its cutoff AED and a smaller number of PM slightly above its cutoff AED than the thoracic sampler (Park, 2005). This comparison is also consistent with the result that USEPA-approved PM_{10} samplers oversampled thoracic PM comparing with RespiCons having an international thoracic curve.

3.4. Microscopic analysis

Images of fly ash were obtained from the filters of TSP and RespiCon samplers to verify the shape and particle size ranges using an environmental scanning electron microscope (ESEM). The collected PM sizes from the stages of RespiCons were shown to agree with the cutoff size for each stage. The ESEM analyses also showed that the sizes of most of the sample images taken from TSP samplers were less than 20 mm with a smooth surface and totally spherical shape. The shape factor was estimated as one on the basis of ESEM images. When the images were obtained from the filters, the electron beam created electrostatic forces between particles sufficient to cause visible particles' displacement between images. These forces may also produce the appearance of clusters or conglomerates on a filter, even though the aerosol may have been sampled as isolated particles from the atmosphere.

4. Conclusions

The performance of six different aerosol samplers was evaluated in terms of mass concentration, PSD, and mass fraction for the international size-sampling conventions. In the present study, two Andersen, four TSP, two RespiCon, four PM_{10}, two DustTrak, and two SidePak samplers were selected and tested by challenging them with polydisperse fly ash spheres having a lognormal distribution with estimated parameters of MMAD = 11.77 μm and GSD = 2.06 in a controlled test chamber. A range of possible true values from all measurements was estimated applying the concept of uncertainty propagation. None of the sampling techniques, standing alone, provided complete estimates of the mass concentration, PSD, and mass fraction for airborne PM in the chamber. The findings in the present study indicate that: (1) Andersens underestimate total suspended PM and overestimate thoracic and respirable PM due to particle bounce and carryover between stages, (2) TSP samplers provide total suspended PM as reference samplers, (3) TSP/CCMs provide no information below an ESD of 2 μm and therefore underestimate respirable PM, (4) RespiCons are free from particle bounce as inhalable samplers, but underestimate total suspended PM, (5) PM_{10} samplers overestimate thoracic PM, and (6) DustTraks and SidePaks provide relative PM concentrations instead of absolute PM concentrations.

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References

American Conference of Governmental Industrial Hygienists (ACGIH), 1999. Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices. ACGIH, Cincinnati, OH, p. 85.

Comité Européen de Normalisation (CEN), 1993. Workplace Atmospheres: Size Fraction Definitions for Measurements of Airborne Particles in the Workplace (CEN standard EN 481). CEN, Brussels, Belgium.

Comité Européen de Normalisation (CEN), 2002. Workplace Atmospheres: Assessment of Performance of Instruments for Mesaurement of Airborne Partice Concentrations (CEN Standard EN 13205). CEN, Brussels, Belgium.

Cushing, K.M., McCain, J.D., Smith, W.B., 1979. Experimental determination of sizing parameters and wall losses of five source-test cascade impactors. Environmental Science & Technology 13, 726–731.

Dunbar, C., Kataya, A., Tiangbe, T., 2005. Reducing bounce effects in the Andersen cascade impactor. International Journal of Pharmaceutics 301, 25–32.

Dzubay, T.G., Hines, L.E., Stevens, R.K., 1976. Particle bounce errors in cascade impactors. Atmospheric Environment 10, 229–234.

Hinds, W.C., 1999. Aerosol Technology Properties, Behavior, and Measurement of Airborne Particles. Wiley Inc., New York, pp. 53–55; 94–97.

Hitzenberger, R., Tohno, S., 2001. Comparison of black carbon (BC) aerosols in two urban areas – concentrations and size distributions. Atmospheric Environment 35 (12), 2153–2167.

Horton, K.D., Ball, M.H.E., Mitchell, J.P., 1992. The calibration of a California measurements PC-2 Quartz Crystal cascade impactor (QCM). Journal of Aerosol Science 23 (5), 505–524.

International Organization for Standardization (ISO), 1995. Air Quality-Particle Size Fraction Definitions for Health-Related Sampling (ISO standard 7708). ISO, Geneva, Switzerland.

Kent, M.S., Robins, T.G., Madl, A.K., 2001. Is total mass or mass of Alveolar-deposited airborne particles of beryllium a better predictor of the prevalence of disease? A preliminary study of a beryllium processing facility. Applied Occupational and Environmental Hygiene 16 (5), 539–558.

May, K.R., 1945. The cascade impactor: an instrument for sampling coarse particles. Journal of Scientific Instruments 22, 187–195.

Mitchell, J.P., Nagel, M.W., 2003. Cascade impactors for the size characterization of aerosols from medical inhalers: their uses and limitations. Journal of Aerosol Medicine 16 (4), 341–377.

National Institute of Occupational Safety and Health (NIOSH), 1994. Particulates not otherwise regulated, Total: method 0500 & Respirable: method 0600. In: Schlecht, P.C., O'Connor, P.F. (Eds.), NIOSH Manual of Analytical Methods, fourth ed. DHHS (NIOSH) Publication, pp. 94–113.

Park, J-M., 2005. Assessment of suspended dust from pipe rattling operations, Appendices E & I – 2 Cutoff size calculation (Andersen sampler), Particle Size Distribution with Prediction Confidence Intervals. Ph.D. dissertation, Texas A&M University, College Station, TX, pp. 4–5; 136–143; 168–180.

Rock, J.C., 1995. Occupational air sampling strategies. In: Cohen, B.S. (Ed.), Air Sampling Instruments, eighth ed. ACGIH, Cincinnati, OH, pp. 19–44. (Chapter 2).

Swanson, P.D., Muzzio, F.J., Annapragada, A., Adjei, A., 1996. Numerical analysis of motion and deposition of particles in cascade impactors. International Journal of Pharmaceutics 142, 33–51.

Taylor, J.R., 1997. An Introduction to Error Analysis. University Science Books, Sausalito, CA, pp. 57–67; 173–179.

Turner, J.R., Hering, S.V., 1987. Greased and oiled substrates as bounce-free impaction surfaces. Journal of Aerosol Science 18, 215–224.

US Environmental Protection Agency (USEPA), 1997. 40 CFR Part 50. National Ambient Air Quality Standards for Particulate Matter.

US Environmental Protection Agency (USEPA), 1988. 40 CFR Part 50. Appendices B & J. Reference Method for the Determination of Suspended Particulate Matter in the Atmosphere (High-Volume Method) & Reference Method for the Determination of Particulate Matter as PM_{10} in the Atmosphere.

US Environmental Protection Agency (USEPA), 2001. 40 CFR Part 53. Ambient air monitoring reference and equivalent methods Subpart D-Procedures for testing performance characteristics of methods for PM_{10}.

Vaughan, N.P., 1989. The Andersen impactor: calibration, wall losses and numerical simulation. Journal of Aerosol Science 20, 67–90.

Wang, L., Wanjura, J.D., Parnell, C.B., Lacey, R.E., Shaw, B.W., 2005. Performance characteristics of a low-volume PM10 sampler. Transactions of the ASAE 48 (2), 739–748.

Wanjura, J.D., Parnell, C.B., Shaw, B.W., Lacey, R.E., 2005. Design and evaluation of a low-volume total suspended particulate sampler. Transactions of the ASAE 48 (4), 1547–1552.