

PERFORMANCE CHARACTERISTICS OF A LOW-VOLUME PM₁₀ SAMPLER

L. Wang, J. D. Wanjura, C. B. Parnell, R. E. Lacey, B. W. Shaw

ABSTRACT. Four identical PM₁₀ pre-separators, along with four identical low-volume ($1 \text{ m}^3 \text{ h}^{-1}$) total suspended particulate (TSP) samplers were tested side-by-side in a controlled laboratory particulate matter (PM) chamber. The four PM₁₀ and four TSP samplers were also tested in an oil pipe cleaning field to evaluate the PM₁₀ samplers' performance characteristics. The PMs used in the chamber tests had mass median diameters (MMDs) larger than $10 \mu\text{m}$, whereas the PM emitted from the oil pipe cleaning system for the field tests had MMD smaller than $10 \mu\text{m}$. The co-located TSP and PM₁₀ sampler testing results indicate that PM₁₀ samplers over-sample when exposed to ambient PM having MMD larger than $10 \mu\text{m}$ aerodynamic equivalent diameter (AED) and under-sample when exposed to ambient PM with MMD smaller than $10 \mu\text{m}$. The over-sampling and under-sampling rates varied with the change of MMD and the PM loading (TSP concentration). The cutpoints and slopes of the PM₁₀ pre-separator changed with the change of MMD of inlet PM.

Keywords. Agricultural PM, Air pollution, Mass median diameter, Particle size distribution, Particulate matter, PM₁₀ sampler, PM₁₀ sampling error, Over-sampling, TSP sampler, Under-sampling.

The National Ambient Air Quality Standards (NAAQS) are the basis for the U.S. Environmental Protection Agency (EPA) to regulate air pollutants, including particulate matter (PM) and five other criteria pollutants. Particles with an aerodynamic equivalent diameter (AED) less than or equal to a nominal $10 \mu\text{m}$ (also known as PM₁₀) and $2.5 \mu\text{m}$ (PM_{2.5}) are the currently accepted indicators for PM pollutants. The EPA-approved PM₁₀ and PM_{2.5} samplers' pre-separators are not 100% efficient, and substantial errors can impact the samplers' concentration measurement. Recent studies have reported that using Federal Reference Method (FRM) PM₁₀ and PM_{2.5} samplers to measure concentrations of PM with a particle size distribution (PSD) characterized by a mass median diameter (MMD) larger than $10 \mu\text{m}$ AED will result in significant over-sampling errors (Buser et al., 2001; Pargmann et al., 2001). Furthermore, Buser et al. (2001) and Pargmann et al. (2001) reported that using FRM PM₁₀ and PM_{2.5} samplers to measure emission concentrations of PM with a MMD smaller than $10 \mu\text{m}$ for the PM₁₀ sampler and $2.5 \mu\text{m}$ for the PM_{2.5} sampler will result in under-sampling errors.

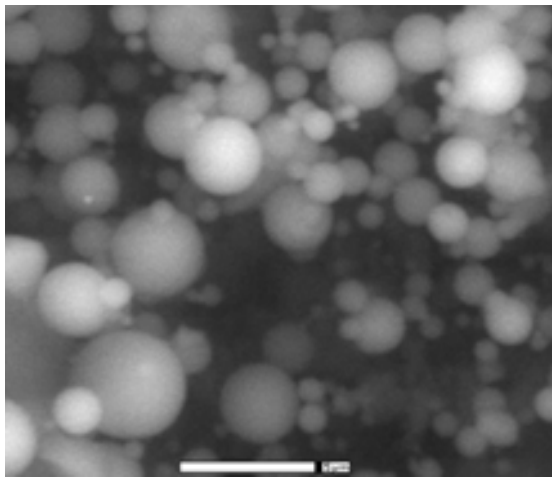
The PM₁₀ inlet (pre-separator) has been used for EPA-approved PM₁₀ samplers and for FRM PM_{2.5} low-volume samplers. A true PM₁₀ pre-separator (true cut) would theoretically remove all particles larger than $10 \mu\text{m}$, allowing only PM less than $10 \mu\text{m}$ to penetrate to the filter. Actual PM₁₀ pre-separators are characterized by performance characteristics (fractional efficiency curve, FEC) that are generally described by a lognormal distribution, which is defined by a cutpoint (d_{50}) and slope. The cutpoint is the AED of the particles collected with 50% efficiency, and the slope of the fractional efficiency curve of the pre-collector is the ratio of the 84.1% and 50% particle sizes ($d_{84.1}/d_{50}$) or the ratio of the 50% and 15.9% particle sizes ($d_{50}/d_{15.9}$) from the FEC (Hinds, 1982).

The Graseby-Andersen FRM PM₁₀ pre-collector was reported to have a d_{50} equal to $10.2 \mu\text{m}$ and a slope of 1.41 with liquid aerosols (McFarland and Ortiz, 1983). The FRM performance standard for PM₁₀ samplers is a cutpoint of $10 \pm 0.5 \mu\text{m}$ (U.S. EPA, 2000) with a slope of 1.5 ± 0.1 . Buser et al. (2001) reported that PM₁₀ measurement errors may be 300% to 500% higher than true PM₁₀ concentrations if the pre-collector is operated within the designed FRM performance standards while sampling PM with a MMD of $20 \mu\text{m}$ and geometric standard deviations (GSD) of 2.0 and 1.5, respectively. Pargmann et al. (2001) reported shifts in pre-separator cutpoints when exposed to PM larger than the designed cutpoint.

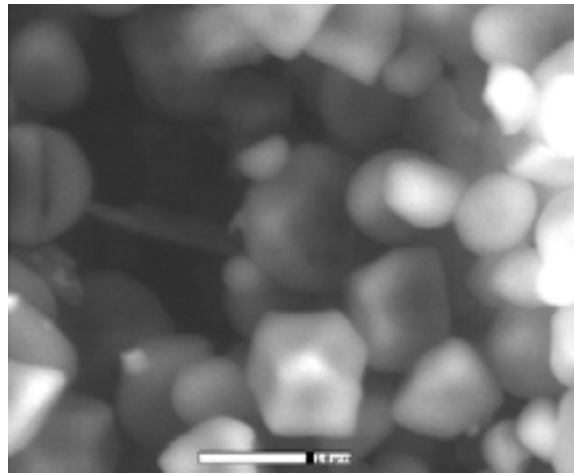
An alternative method of determining PM₁₀ concentrations is to combine total suspended particulate (TSP) concentrations and PSD analyses. Using this method, the PM₁₀ concentration equals the TSP concentration times the mass fraction of PM less than $10 \mu\text{m}$ obtained from the PSD. The EPA high-volume TSP sampler operates at an average volume flow rate of $85 \text{ m}^3 \text{ h}^{-1}$ (50 cubic feet per minute, or cfm) (U.S. EPA, 1987). According to Boriack et al. (2003), the TSP high-volume sampler's flow rate is highly variable, which is generally attributed to increases in filter loading. In

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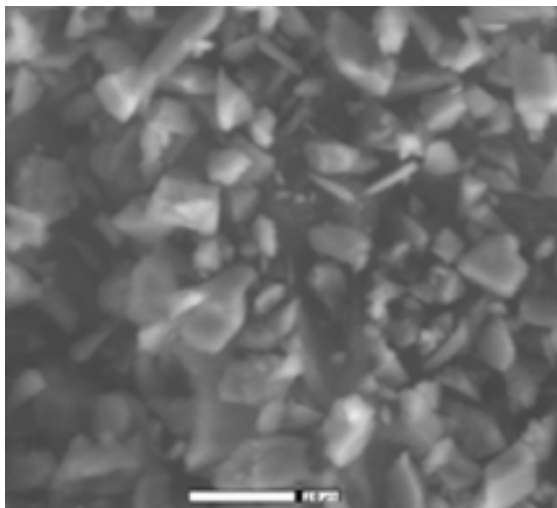
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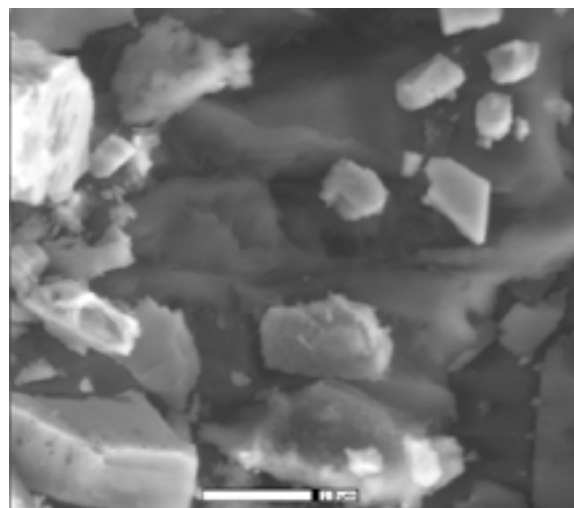
Fly ash



Cornstarch



Aluminum oxide



Dust from oil pipe cleaning system

Figure 1. SEM photos for testing PM.

fact, it is becoming more common practice to measure PM concentrations on a low-volume basis (Wanjura et al., 2003), i.e., a volume flow rate of $1 \text{ m}^3 \text{ h}^{-1}$. Wanjura et al. (2003) at Texas A&M University (TAMU) designed and built a new low-volume TSP sampler based on EPA's engineering design parameters for TSP samplers, listed in EPA 40 CFR Part 50 (U.S. EPA, 1987). Wanjura et al. (2003) conducted a side-by-side test of the TAMU low-volume TSP samplers and EPA high-volume TSP samplers and reported excellent agreement between TSP concentration and PSD measurements from both samplers. In this research, the TAMU low-volume TSP samplers were compared with PM_{10} samplers to evaluate the PM_{10} over-sampling problem.

The hypotheses of this research were that: (1) the PM_{10} pre-separator performance characteristics will vary as the PSD of the PM being sampled is varied, and (2) PM_{10} sampler concentration measurement will be significantly larger than "true PM_{10} " concentrations when sampling with MMD values larger than $10 \mu\text{m}$ AED. The goals of this research were to evaluate the performance characteristics of the PM_{10} pre-separator while sampling agricultural PM, as well as "simulated" urban PM, and to identify sources of sampling errors.

MATERIALS AND METHODS

TESTING MATERIALS

In order to evaluate the PM_{10} inlet sampling error and to determine the interaction between the PM_{10} inlet performance characteristics and PM PSD characteristics, three kinds of PM with different MMD values were used. Cornstarch was used to represent agricultural PM, fly ash was used to represent industrial PM (i.e., power plant PM), and aluminum oxide, the smallest PM, was used to represent "urban" PM. A Coulter Counter Multisizer (CCM) (Coulter Multisizer III, Beckman Coulter, Inc., Fullerton, Cal.) was used to determine the PSD values of the testing PM. CCM particle size analysis gives a PSD in the form of particle volume (or mass) versus equivalent spherical diameter (ESD). Equation 1 was used to convert ESD to AED (Hinds, 1999), and the particle densities of each PM were measured using a pycnometer (AccuPyc 1330, Micromeritics, Norcross, Ga.):

$$\text{AED} = \text{ESD} * \sqrt{\frac{\rho}{\chi}} \quad (1)$$

where

AED = particle aerodynamic equivalent diameter (μm)

ESD = particle equivalent spherical diameter (μm)

ρ = particle density (g cm^{-3})

χ = particle shape factor ($\chi = 1$ for spherical particle).

The particle densities for cornstarch, fly ash, and aluminum oxide were 1.5 g cm^{-3} , 2.7 g cm^{-3} , and 3.9 g cm^{-3} , respectively. Cornstarch had a MMD of $19 \mu\text{m}$ (AED) and GSD of 1.4. Fly ash had a MMD of $12 \mu\text{m}$ and GSD of 1.7. Aluminum oxide had a MMD of $8.4 \mu\text{m}$ and GSD of 1.4.

Fly ash, cornstarch, and aluminum oxide particles were examined under a scanning electron microscope (SEM) (ESEM E3, Electroscan, Inc., Wilmington, Mass.) in order to determine a particle shape factor estimate for testing PM. The ElectronScan ESEM E3 operates in a magnification range of 100X to 100,000X and has a guaranteed resolution of 5.0 nm. In figure 1, fly ash and cornstarch particles appear nearly spherical, while the aluminum oxide particles appear angular in shape. Pargmann (2001) reported that the shape factor for aluminum oxide particles was 1.44.

During this study, PM_{10} and TSP samplers were exposed, in a side-by-side test, to PM generated from an oil pipe cleaning facility. The PM emitted from the cleaning system had a particle density of 2.5 g cm^{-3} , MMD of $8 \mu\text{m}$ (AED), and GSD of 2.2. It was assumed that this PM had the shape factor of 1.44, the same as aluminum oxide PM, since the SEM photo of this PM (fig. 1) showed that it had a similar irregular shape as aluminum oxide PM.

SAMPLERS AND SAMPLING SYSTEMS

Four identical Graseby-Andersen FRM PM_{10} pre-separators and four identical TAMU low-volume TSP samplers were tested side-by-side in a controlled PM chamber. This is also known as co-located PM_{10} and TSP testing. Figure 2 shows the vertical locations of the samplers. There was a 33 cm (13 in.) height difference between the PM_{10} sampler inlets and the TSP sampler inlets. It was assumed that PM concentration in the chamber was constant because of air mixing in the first 45° transition part of the chamber before passing into the cube body of the chamber.

Five 1 h duration replications were conducted for each PM. The chamber was manually cleaned before new PM was introduced. Because of heavy loading, the impaction surfaces of the PM_{10} inlets were manually cleaned prior to each run to minimize the sampling error caused by PM carryover.

Schematics of the TSP and PM_{10} sampling systems are shown in figures 3 and 4. An orifice meter, pressure transducer, and an adjustable needle valve were used to monitor and maintain a constant airflow rate during the 1 h tests. The target flow rate through the PM_{10} inlets and low-volume TSP samplers was one cubic meter per hour ($1 \text{ m}^3 \text{ h}^{-1}$). The equipment used in the sampling system is listed in the table 1.

Figures 5 and 6 show the chamber design and the sampler location inside the chamber. In the low-volume TSP and PM_{10} sampling systems, the pump pulled the PM-entrained air through a TSP or PM_{10} inlet and then through a Teflon filter. The PM, which penetrated the TSP or PM_{10} inlet, was captured on the filter, and the filtered air was discharged. An orifice meter was used to monitor the flow rate by monitoring the pressure drop across the orifice meter. The following equation was used to set the proper pressure drop across the orifice meter based on the target flow rate of $1 \text{ m}^3 \text{ h}^{-1}$:

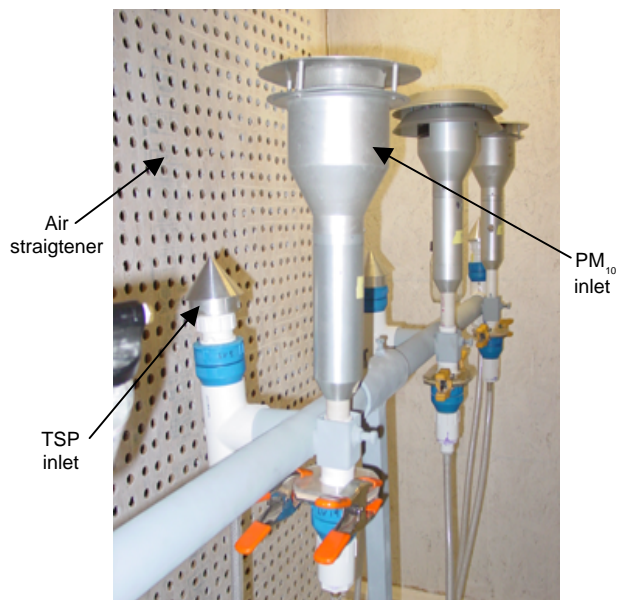


Figure 2. View of the sampler location inside the PM chamber and air straightener.

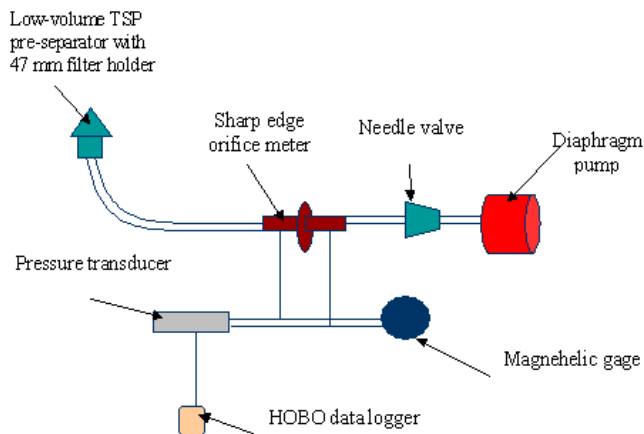


Figure 3. Low-volume TSP sampling system.

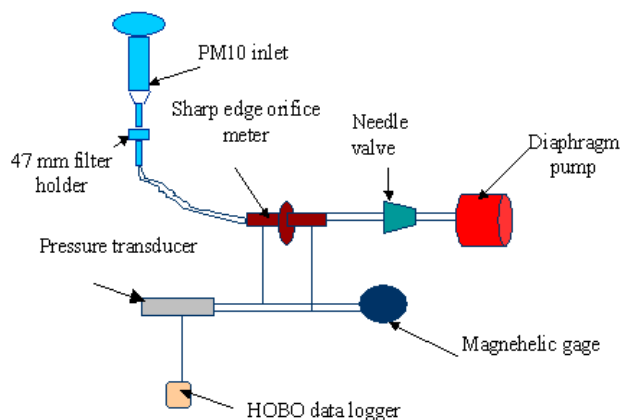


Figure 4. Low-volume PM_{10} sampling system.

Table 1. Equipment used for the PM₁₀ and TSP sampling systems.

Equipment	Manufacturer and Model	Parameters
PM ₁₀ inlet	Graseby-Andersen SA246B	1 m ³ h ⁻¹ flow rate
TSP inlet	Made in-house	1 m ³ h ⁻¹ flow rate; tested with no significant difference compared to EPA high-volume TSP sample (Wanjura et al., 2003)
Sharp-edge orifice meter	Made in-house	Calibrated with Meriam laminar flow element; accuracy = ±0.7% reading; range = 0 to 3.11 m ³ min ⁻¹
Differential pressure transducer	Omega Engineering PX274	Output = 4-20 mA; accuracy = ±1.0% of full scale; proof pressure = 10 psi
Data logger	HOBO H8 RH/Temp/2x External, Onset Computer Corp.	Range = 0 to 20 mA; accuracy = ±1% of full scale
Magnehelic differential pressure gauges	Dwyer Instruments	Range = 0 to 1245 Pa (0 to 5 in. w.g.); accuracy = ±24.9 Pa (0.1 in. w.g)
Needle valve	Cole-Parmer A-68831-00	Brass, 4.1 × 10 ⁶ Pa (600 psi) max. pressure
Diaphragm pump	Dayton 4Z792	1/12 HP, 60 Hz, 115 V, 2.0 A; max. flow = 1.95 m ³ h ⁻¹ @ 0 Pa (1.15 ft ³ min ⁻¹ @ 0 in. Hg); min. flow = 0.82 m ³ h ⁻¹ @ 33858 Pa (0.48 ft ³ min ⁻¹ @ 10 in. Hg)
Filter	PTFE Teflon	47 mm diameter

$$Q = 1.252 * 10^4 * K * D_o^2 * \sqrt{\frac{\Delta P}{\rho_a}} \quad (2)$$

where

Q = airflow rate through the orifice meter (m³ h⁻¹)

K = flow coefficient (dimensionless)

D_o = orifice diameter (m)

ΔP = pressure drop across the orifice (mm H₂O)

ρ_a = air density (kg m⁻³).

The pressure drop across the orifice meter was measured with a pressure transducer. A HOBO data logger (H8 RH/Temp/2X External, Onset Computer Corp., Pocasset, Mass.) was used to record the output from the pressure transducer at 12 s interval. This output was used to calculate instantaneous volumetric flow rate. A magnehelic differential pressure gauge was used for a visual check of the pressure drop across orifice meter during the testing period. A needle valve in the sampling system was used to adjust the flow rate to keep a constant volumetric flow of 1 m³ h⁻¹ through the sampler inlet when change in the pressure drop across orifice meter was observed. Only a couple of adjusting times occurred due to heavy loading on the filter. The change in flow rate was controlled in a range of less than 1%.

Barometric pressure, air temperature, and relative humidity were monitored by a digital weather station (Perception II, Davis Instruments, Hayward, Cal.) for calculating the air density. Combining this density and the pressure drop measured by the pressure transducer, flow rates were calculated using equation 2 to determine the total volume of air pulled through the system during each 1 h testing period using air density and measured pressure drop. These flow volumes were used to calculate the PM concentration that penetrated the PM₁₀ or TSP sampler pre-separator.

PTFE Teflon filters (47 mm) were used for the PM₁₀ and TSP low-volume inlets. After each test, the filters were placed in plastic petri dishes to prevent handling contamination. The filters were conditioned before and after testing in a weighting room for 24 h at 25 °C and 46% relative humidity, as specified by the EPA, and weighed with a microbalance (range: 0 to 101 mg, accuracy: ±0.1 mg) that was located in the weighting room. Each filter was weighted three times, and the mean of the three measurements was used to

determine the mass captured on the filter for PM₁₀ or TSP concentration calculations.

Concentration and PSD measurements from the TSP samplers were used to determine the concentration and PSD characteristics of the PM in the chamber for each test.

CONTROLLED PM CHAMBER FOR FIRST LABORATORY TESTS

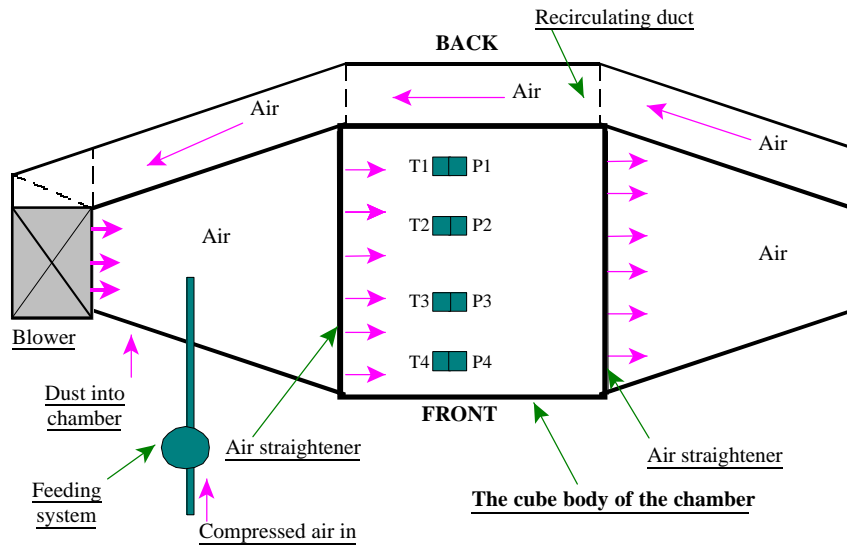
Figure 5 shows the top view of the PM chamber used in this research. The PM chamber was initially designed and built for Pargmann's research (2001). It included an external PM feeding system to inject PM into the chamber with compressed air. The chamber consisted of a cube body portion measuring 2.4 m at each dimension, with two 45° transitions located on opposite ends of the cube. A single inlet blower located at the end of one transition was capable of moving air at a rate of 128 m³ min⁻¹ through the chamber. A duct connected to the opposite transition allowed PM particles to travel around the outside of the dust chamber body and into the inlet of the fan, to be re-circulated throughout the chamber. Perforated walls, with an 18% open area, served as airflow straighteners between each transition and the cube body.

CONTROLLED PM CHAMBER FOR SECOND LABORATORY TESTS

After the first set of laboratory tests, it was determined that the PM concentration distributions in the chamber were not uniform in the front half of the chamber. The PM feeding system was modified, as shown in figure 6, to improve the concentration distribution in the chamber; meanwhile, the TSP samplers were raised to the same height as the PM₁₀ samplers. Three more tests with fly ash were run to evaluate this adjustment.

FIELD SAMPLING SETUP

Field tests were conducted in collaboration with the Nuclear Engineering Department at TAMU. The source was an oil pipe cleaning system at the Riverside campus of TAMU. In this system, a rotary scraper, driven by compressed air, was inserted into the pipe to clean the inside surface. PM was emitted from the end of the pipe. At the same time as the inside surface was being cleaned, a metal brush



- | | |
|----------------------|-----------------------------------|
| T1: low-volume TSP 1 | P1: low-volume PM ₁₀ 1 |
| T2: low-volume TSP 2 | P2: low-volume PM ₁₀ 2 |
| T3: low-volume TSP 3 | P3: low-volume PM ₁₀ 3 |
| T4: low-volume TSP 4 | P4: low-volume PM ₁₀ 4 |

Figure 5. Top view of the PM chamber and sampler setup (co-located TSP and PM₁₀ testing systems).

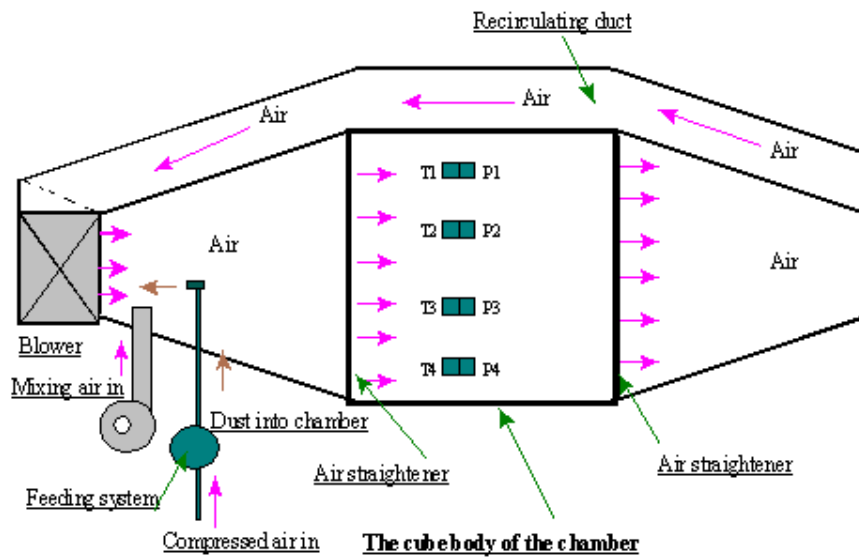


Figure 6. Top view of the PM chamber with modified PM-feeding system.

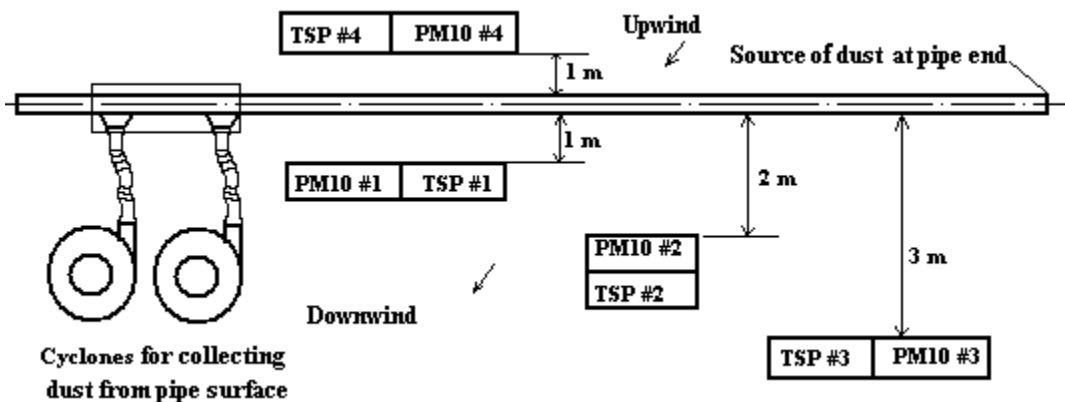


Figure 7. Schematic of the oil pipe cleaning system and PM sampler locations.



Figure 8. View of PM plume from oil pipe.

was cleaning the outside surface of the pipe. Two cyclones were used to collect the rusty PM from the outside surface of the pipe. Four PM₁₀ and four TSP samplers were placed side-by-side at 1, 2, and 3 m from the cleaning system, as shown in the figures 7 and 8.

DATA ANALYSES

TSP and PM₁₀ Concentration Calculations

TSP and PM₁₀ concentrations were determined by dividing the mass captured on the filter by the total volume of air pulled through the sampler during the 1 h sampling period. The following equation was used for the concentration calculations:

$$C = \frac{\Delta M}{\sum Q * t} \quad (3)$$

where

- C = 1 h concentration (mg m⁻³)
- ΔM = mass captured on the filter (= pre-weight of filter – post-weight of filter, mg)
- Q = 12 s airflow rate through the orifice meter (m³ s⁻¹)
- t = time interval for the data logger to read the measurement data through pressure transducer (12 s).

PM₁₀ Inlet Fractional Collection Efficiency Curve Calculation

A fractional efficiency curve describes the percent mass captured versus particle size. Four parameters were obtained to develop the PM₁₀ sampler's fractional efficiency curve:

- Inlet PM concentration: PM concentrations measured by the TSP samplers.
- Inlet PSD: PSD of PM captured on the TSP sampler filter.
- Emission (outlet) concentration: PM concentrations measured by the PM₁₀ samplers.
- Outlet PSD of PM captured on the PM₁₀ filter.

The inlet and outlet concentrations for the various size ranges were calculated using inlet and outlet PM concentrations and fractions of PM in those size ranges obtained from the Coulter Counter PSD analysis. The outlet concentrations

were divided by the corresponding inlet concentrations for each size range and subtracted from 1, as shown in equation 4, with the resulting values being the fractional efficiencies for each size range:

$$\eta_j = \left(1 - \frac{C_{oj}}{C_{ij}} \right) \quad (4)$$

where

- η_j = fractional efficiency of j th size range
- C_{oj} = outlet concentration of j th size range
- C_{ij} = inlet concentration of j th size range.

As indicated by Hinds (1982), the fractional efficiency curve is most commonly represented by a lognormal distribution with a cutpoint and a slope. The cutpoint is the particle size at which 50% of PM is captured and 50% penetrates to the filter. The slope is the ratio of the 84.1% and 50% particle sizes, or the ratio of the 50% and 15.9% particle sizes, or the square root of the ratio of the 84.1% and 15.9% particle size from the fractional efficiency curve.

Over-Sampling Rate Calculation

Buser et al. (2001) reported on the inherent sampling errors associated with EPA-approved PM₁₀ samplers. Over-sampling will occur when a PM₁₀ sampler is exposed to a PM with MMD larger than 10 μ m. The over-sampling rate (%) for the PM₁₀ sampler was determined using the following equation:

$$\varepsilon = 100 * \left(\frac{R_m - R_t}{R_t} \right) \quad (5)$$

where

- ε = over-sampling rate (%)
- R_m = measured PM₁₀/TSP ratio
- R_t = true PM₁₀/TSP ratio.

In equation 5, the measured PM₁₀/TSP ratio is the ratio of PM₁₀ and TSP concentrations measured by the PM₁₀ and TSP samplers. The true PM₁₀/TSP ratio is the PM₁₀ mass fraction obtained from the PSD of PM captured on the TSP sampler filter.

Table 2. Measured 1 h concentrations (mg m⁻³) of PM₁₀ and TSP.

PM	Test	PM ₁₀ Samplers				TSP Samplers			
		P1	P2	P3	P4	T1	T2	T3	T4
Cornstarch	1	15	20	18	15	22	10	46	42
	2	19	25	22	19	32	54	73	63
	3	10	13	13	11	14	25	38	32
	4	12	14	12	13	16	29	44	39
	5	7	9	8	8	10	17	26	31
	Mean ^[a]		13 a	16 a	15 a	13 a	19 a	27 b	45 d
Aluminum oxide	6	19	24	22	19	12	21	25	22
	7	28	31	34	30	18	30	38	33
	8	33	41	40	35	17	38	45	39
	9	39	49	45	41	26	42	52	46
	10	35	47	40	34	21	37	47	42
	Mean		31 b	38 c	36 c	32 b	19 a	34 b	41 d
Fly ash	11	52	66	55	50	38	68	62	67
	12	39	46	35	36	24	46	45	42
	13	34	45	35	33	27	41	42	41
	14	24	33	26	23	19	30	29	28
	15	25	32	25	24	17	29	30	29
	Mean		35 c	44 d	35 d	33 c	25 b	43 d	42 d

^[a] Means followed by the same letter are not significantly different at the 0.05 level.

In addition to the over-sampling problem associated with the PM₁₀ sampler, Buser et al. (2001) reported that under-sampling will occur when a PM₁₀ sampler is exposed to a PM with a MMD smaller than 10 μm. Equation 5 can also be used to evaluate an under-sampling rate.

EXPERIMENTAL DESIGN

This study was statistically analyzed as a factorial experiment consisting of two factors (inlet dust and samplers). Five replications were run for each dust, with a total of 150 observations. Each replication corresponded to 1 h sampling time. Standard analysis of variance (ANOVA) tests were conducted to determine the statistical difference among the samplers by Tukey's Studentized range (HSD) test at a 95% confidence interval.

RESULTS AND DISCUSSION

FIRST LABORATORY TEST RESULTS

PM Concentration Measurements

Table 2 lists the resulting PM concentration measurements from the first set of laboratory tests utilizing the PM₁₀ and TSP samplers. There were considerable variations in the concentrations measured by the four identical TSP samplers. The significant differences between the TSP measurements indicate that there was a horizontal concentration gradient across the chamber in the perforated wall direction. However, the concentration difference between T3 and T4 was not significant. This suggests that the concentration in the front half of the chamber (see fig. 5 for front-side definition) was horizontally constant.

In the back half of the chamber, the PM₁₀ measurements were higher than the TSP measurements for aluminum oxide and fly ash dusts. The PM₁₀ concentrations cannot be higher than the corresponding TSP concentrations if both samplers were exposed to the same PM at the same concentration. The only reason that the PM₁₀ measurements could be higher than the TSP measurements is if a vertical concentration gradient

existed in the chamber. In this test, there was a 33 cm (13 in.) height difference between the PM₁₀ and TSP inlets. It was also observed the outlet end of the plastic tube, used to inject dust into the chamber using compressed air, was located between sampler T2 and T3 and was pointing upward. It was assumed that the compressed air was not well mixed with the chamber's main airflow source. This caused a PM plume flowing toward the backside of the chamber and upward. As a result, the PM in the back half of chamber was not uniformly distributed. This generated a concentration gradient in both the horizontal and the vertical directions in the back half of the chamber. In the front half of the chamber, there was no compressed air impacting on the PM plume. The PM concentrations were constant (see T3 and T4 measurements in table 2). These observations suggest that the PM chamber used in this research was a semi-constant concentration PM chamber, which means that PM concentration was uniform in the front half of the chamber, but a concentration gradient existed in the back half. As a result, only data measured by the P3, T3, P4, and T4 samplers were used for PM₁₀ characteristics analyses.

PM₁₀ /TSP Ratio Measurements and Over-Sampling Rates

Tables 3 and 4 list the ratio of PM₁₀ to TSP concentration measurements and the average over-sampling rates. The average PM₁₀ fractions determined by using the PM₁₀/TSP ratio from co-located P3/T3 and P4/T4 samplers were 32%, 88% and 83% for corn starch, aluminum oxide, and fly ash, respectively. The average fractions obtained from the Coulter Counter PSD values from the TSP samplers (considered true PM₁₀) were 17%, 77%, and 59% for cornstarch, aluminum oxide, and fly ash, respectively. The comparison of the measured PM₁₀/TSP ratios to the true PM₁₀/TSP ratios indicated the over-sampling of PM₁₀ samplers. These PM₁₀ over-sampling rates increased as the MMD of the dust increased, as shown in table 4. Data listed in table 4 also suggest that the GSD of PSD was another factor that may impact PM₁₀ over-sampling rate.

Table 3. Comparison of measured PM₁₀/TSP ratio (%) and the true PM₁₀/TSP ratio (%).

PM	Test	Co-Located PM ₁₀ and TSP Samplers P3 and T3				Co-Located PM ₁₀ and TSP Samplers P4 and T4			
		Measured P3 Conc. (mg m ⁻³)	Measured T3 Conc. (mg m ⁻³)	Measured ^[a] PM ₁₀ /TSP (%)	True ^[b] PM ₁₀ /TSP (%)	Measured P4 Conc. (mg m ⁻³)	Measured T4 Conc. (mg m ⁻³)	Measured PM ₁₀ /TSP (%)	True PM ₁₀ /TSP (%)
Cornstarch	1	18	46	39	22	15	42	36	25
	2	22	73	30	18	19	63	30	16
	3	13	38	34	12	11	32	34	13
	4	12	44	27	12	13	39	33	19
	5	8	26	31	15	8	31	26	15
	Mean ^[c]			32 a	16 b			32 a	18 b
Aluminum Oxide	6	22	25	88	58	19	22	86	63
	7	34	38	89	80	30	33	91	80
	8	40	45	89	84	35	39	90	79
	9	45	52	87	85	41	46	89	80
	10	40	47	85	76	34	42	81	82
	Mean			88 c	77 d			87 c	77 d
Fly ash	11	55	62	89	48	50	67	75	51
	12	35	45	78	51	36	42	86	62
	13	35	42	83	66	33	41	80	65
	14	26	29	90	57	23	28	82	61
	15	25	30	83	68	24	29	83	64
	Mean			85 c	58 d			81 c	60 d

^[a] Measured PM₁₀/TSP ratio is the ratio of the PM₁₀ and TSP concentrations measured by the respective samplers.

^[b] True PM₁₀/TSP ratio is the PM₁₀ mass fraction obtained from the PSD of PM captured on the TSP sampler filter.

^[c] Means followed by the same letter are not significantly different at the 0.05 level.

Table 4. Average PM₁₀ over-sampling rates (%).

PM	MMD (μm) ^[a]	GSD ^[b]	Over-Sampling Rates (%)	
			P3	P4
Cornstarch	15.93	1.60	100	78
Fly ash	10.58	2.04	46	35
Aluminum oxide	10.38	1.92	14	14

^[a] The average PSD MMD (AED) of the PM captured on the TSP sampler filters; it is not the MMD of the original PM.

^[b] The average PSD SGD of the PM captured on the TSP sampler filters; it is not the GSD of the original PM.

Table 5. PM₁₀ inlets cutpoints (μm) and slopes.^[a]

Dust	Test	P3		P4	
		Cutpoint (μm)	Slope	Cutpoint (μm)	Slope
Cornstarch	1	12.5	1.3	12.0	1.3
	2	11.5	1.4	12.5	1.3
	3	13.2	1.3	13.2	1.3
	Mean ^[b]	12.4 a	1.3	12.6 a	1.3
Aluminum Oxide	6	18.0	1.4	16.0	1.4
	7	17.0	1.5	17.0	1.5
	8	18.0	1.5	16.0	1.6
	Mean	17.6 b	1.5	16.3 b	1.5
Fly ash	11	17.5	1.3	18.5	1.3
	12	17.0	1.5	19.0	1.6
	13	17.0	1.5	17.0	1.5
	Mean	17.2 b	1.4	18.2 b	1.5

^[a] Cutpoints and slopes were obtained from fractional efficiency curves, which were calculated using inlet and outlet concentration and PSD values (eq. 4). For P3, inlet concentration and PSD were obtained from its co-located TSP sampler's (T3) measurements. For P4, inlet concentration and PSD were obtained from its co-located TSP sampler's (T4) measurements.

^[b] Means followed by the same letter are not significantly different at the 0.05 level.

Cutpoints and Slopes of PM₁₀ Inlets

Based on the TSP and PM₁₀ concentrations and the PSD values of PM captured on the TSP and PM₁₀ filters, the fractional efficiency curves of the PM₁₀ inlets were calculated using equation 4. Cutpoints and slopes were determined from the fractional efficiency curves. Table 5 shows the PM₁₀ inlet cutpoints and slopes for each PM. The statistical analysis indicates that the average cutpoints and slopes of P3 and P4 are not significantly different for cornstarch, aluminum oxide, and fly ash. The calculated data indicates that the cutpoint increased as the PM MMD decreased. It should be emphasized that a shift in the PM₁₀ sampler cutpoint beyond 10 ± 0.5 μm (AED) will significantly increase measurement errors. All sampler cutpoints for the three PMs are outside of established PM₁₀ sampler tolerances.

SECOND LABORATORY TEST RESULTS

The second set of laboratory test results are listed in table 6. The four TSP (T1 to T4) samplers' concentrations were not statistically different. This indicates that the modified dust feeding system produced uniform concentration in the chamber. There were significant differences among the four PM₁₀ samplers (P1, P2, P3, and P4) as well as the over-sampling rates for the four PM₁₀ samplers. PM₁₀ sampler inlet loading rates were indicated by PM concentrations around PM₁₀ samplers, which were measured by the co-located TSP samplers. The higher TSP concentration indicates the higher inlet loading rate. Results in table 6 indicate that the over-sampling rates may vary with the change in the PM loading. Further study of this observation remains to be done to quantify the changes.

FIELD SAMPLING RESULTS

The field sampling results are included in the tables 7 and 8. As shown in figure 7, TSP samplers 1, 2, and 3 were located

Table 6. Second laboratory test results with fly ash PM: Measured 1 h concentration (mg m⁻³), PM₁₀/TSP ratio (%), and over-sampling rate (%).^[a]

Test	Co-Located PM ₁₀ and TSP Samplers P1 and T1					Co-Located PM ₁₀ and TSP Samplers P2 and T2				
	Measured P1 Conc. (mg m ⁻³)	Measured T1 Conc. (mg m ⁻³)	Measured PM ₁₀ /TSP (%) ^[b]	True PM ₁₀ /TSP (%) ^[c]	Over-Sampling Rate (%) ^[d]	Measured P2 Conc. (mg m ⁻³)	Measured T2 Conc. (mg m ⁻³)	Measured PM ₁₀ /TSP (%)	True PM ₁₀ /TSP (%)	Over-Sampling Rate (%)
1	26	34	76	65	17	34	35	97	61	59
2	17	24	71	60	18	24	25	96	66	45
3	22	25	88	71	24	24	26	92	62	48
Mean			78		20			95		50

Test	Co-Located PM ₁₀ and TSP Samplers P3 and T3					Co-Located PM ₁₀ and TSP Samplers P4 and T4				
	Measured P3 Conc. (mg m ⁻³)	Measured T3 Conc. (mg m ⁻³)	Measured PM ₁₀ /TSP (%)	True PM ₁₀ /TSP (%)	Over-Sampling Rate (%)	Measured P4 Conc. (mg m ⁻³)	Measured T4 Conc. (mg m ⁻³)	Measured PM ₁₀ /TSP (%)	True PM ₁₀ /TSP (%)	Over-Sampling Rate (%)
1	26	32	81	67	21	-- ^[e]	--	--	--	--
2	19	26	73	65	12	18	25	72	59	22
3	21	30	70	--	--	20	30	67	55	22
Mean			75		17			83		22

^[a] See figures 5 and 6 for sampler locations.

^[b] Measured PM₁₀/TSP ratio is the ratio of the PM₁₀ and TSP concentrations measured by the respective samplers.

^[c] True PM₁₀/TSP ratio is the PM₁₀ mass fraction obtained from the PSD of PM captured on the TSP sampler filter.

^[d] Over-sampling rates were determined by equation 5.

^[e] Indicates no PSD measurement because the filter was used for SEM photo analyses.

Table 7. Field-testing results with the dust emitted from an oil pipe cleaning system: measured concentration (mg m⁻³), PM₁₀/TSP ratio (%) and over-sampling rate (%).^[a]

Testing Date (2003)	Co-Located PM ₁₀ 1 and TSP 1 Samplers					Co-Located PM ₁₀ 2 and TSP 2 Samplers				
	Measured PM ₁₀ 1 Conc. (mg m ⁻³)	Measured TSP 1 Conc. (mg m ⁻³)	Measured PM ₁₀ /TSP (%) ^[b]	True PM ₁₀ /TSP (%) ^[c]	Over-Sampling Rate (%) ^[d]	Measured PM ₁₀ 2 Conc. (mg m ⁻³)	Measured TSP 2 Conc. (mg m ⁻³)	Measured PM ₁₀ /TSP (%)	True PM ₁₀ /TSP (%)	Over-Sampling Rate (%)
16 June	2.8	12.7	22	81	-73	5.1	12.9	39	84	-54
17 June	2.2	8.1	27	52	-48	2.7	11.5	23	79	-71
Mean			25		-61			31		-63

Testing Date	Co-Located PM ₁₀ 3 and TSP 3 Samplers					Co-Located PM ₁₀ 4 and TSP 4 Samplers				
	Measured PM ₁₀ 3 Conc. (mg m ⁻³)	Measured TSP 3 Conc. (mg m ⁻³)	Measured PM ₁₀ /TSP (%)	True PM ₁₀ /TSP (%)	Over-Sampling Rate (%)	Measured PM ₁₀ 4 Conc. (mg m ⁻³)	Measured TSP 4 Conc. (mg m ⁻³)	Measured PM ₁₀ /TSP (%)	True PM ₁₀ /TSP (%)	Over-Sampling Rate (%)
16 June	-- ^[e]	1.6	--	76	--	0.27	0.35	77	xx ^[f]	xx
17 June	1.6	5.8	28	62	-55	0.26	0.57	46	xx	xx
Mean			28		-55			62		--

^[a] See figures 7 and 8 for sampler locations; PM₁₀ 4 and TSP 4 were located at upwind, whereas PM₁₀ 1 and TSP 1, PM₁₀ 2 and TSP 2, and PM₁₀ 3 and TSP 3 were located at downwind.

^[b] Measured PM₁₀/TSP ratio is the ratio of the PM₁₀ and TSP concentrations measured by the respective samplers

^[c] True PM₁₀/TSP ratio is the PM₁₀ fraction of PSD from TSP sampler measurements.

^[d] Over-sampling rates were determined by equation 5; a negative over-sampling rate indicates an under-sampling problem.

^[e] Indicates no PM₁₀ measurement. As a result, no measured PM₁₀/TSP ratio obtained, nor over-sampling rate.

^[f] Indicates not enough PM on the filter to run the Coulter Counter for PSD measurements. As a result, no true PM₁₀/TSP ratio was obtained.

Table 8. Measured PSD of the PM captured on TSP sampler filters in the testing field.^[a]

Testing Date	TSP 1		TSP 2		TSP 3		TSP 4	
	MMD (μm) ^[b]	GSD ^[c]	MMD (μm)	GSD	MMD (μm)	GSD	MMD (μm)	GSD
16 June 2003	5.9	1.7	5.5	1.7	6.1	1.9	-- ^[d]	--
17 June 2003	9.6	2.4	6.3	1.8	8.0	2.2	--	--

^[a] See figures 7 and 8 for sampler locations.

^[b] MMD is the MMD (AED) of PSD on the TSP sampler filter.

^[c] GSD is the GSD of PSD on the TSP sampler filter.

^[d] Indicates not enough PM on the filter to run Coulter Counter for PSD measurements.

downwind, and TSP sampler 4 was located upwind. Concentration differences due to sampler location, attributed to PM dispersion, were detected. The results from co-located TSP and PM₁₀ samplers were used to evaluate the PM₁₀ samplers. It is observed that the MMD of PM on the TSP filters was different at different locations (table 8). The PM con-

centrations on the upwind sampler filters were too low to run PSD analysis. The MMD values of the PM from the oil pipe cleaning system were smaller than 10 μm (table 8); as a result, an under-sampling problem occurred. In fact, the negative over-sampling rates, shown in table 7, suggest under-sampling. PM₁₀ sampler inlet loading rates were indicated by PM

concentrations around the PM₁₀ samplers, which were measured by the co-located TSP samplers. The higher TSP concentration indicates the higher inlet loading rate. The under-sampling rate may also change with the change in PM loading. Since only two sampling events were conducted in the field, there was no statistical analysis for these measurements. Further field sampling research is needed to verify the conclusion from the field sampling study in this research.

CONCLUSIONS

The experimental test results in this research demonstrate that characteristics of PM, such as MMD and GSD, have great impact on PM₁₀ sampler performance. PM₁₀ samplers over-sampled when exposed to ambient PM having MMD values larger than 10 µm AED, and they under-sampled when exposed to ambient PM having MMD values smaller than 10 µm AED. PM₁₀ sampler over-sampling rates increase as the MMD of the PM being sampled increases, while the under-sampling rates increase as the MMD of the PM being sampled decreases. The amount of over-sampling or under-sampling increased as the MMD moved further from 10 µm.

PM₁₀ over-sampling and under-sampling rates may change with PM loading into the PM₁₀ sampler (indicated by TSP concentrations), but further study on this observation remains to be done to quantify the changes.

The cutpoints and slopes of the PM₁₀ pre-separator changed with the changes in the MMD of the PM being sampled. Cutpoint increased as the MMD of the PM being sampled decreased. The fractional efficiency curve shifted to the right as the MMD of the PM being sampled decreased.

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