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Performance Characteristics of Low-Volume PM_{10} Inlet and TEOM Continuous PM Sampler

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Abstract. *Four identical PM_{10} pre-separators, along with four identical low-volume ($1m^3/hr$) total suspended particulate (TSP) samplers and two Tapered Element Oscillation Method (TEOM) samplers-one with TSP inlet, one with PM_{10} inlet were tested side-by-side in a controlled laboratory dust chamber. The four PM_{10} and four TSP samplers were also tested in an oil pipe-cleaning field to evaluate the PM_{10} sampler's performance characteristics. The dusts used in the chamber tests had MMD's larger than 10 μm, whereas the dust emitted from oil pipe cleaning system for the field tests had MMD's smaller than 10 μm. The co-located TSP/PM_{10} sampler testing results indicate that PM_{10} samplers over-sample when exposed to ambient PM having mass median diameters (MMD's) larger than 10 μm aerodynamic equivalent diameter (AED) and under-sample when exposed to ambient PM with MMD smaller than 10 μm. The over-sampling / under-sampling rates varied with the change of MMD and the dust loading (TSP concentration). The cut-points and slopes of the PM_{10} pre-separator changed with the change of MMD's of inlet particulate matter (PM). The comparison of TEOM and TSP results indicates that TEOM/TSP yielded excellent agreement measurement with TSP samplers.*

Keywords. Air pollution, particulate matter, PM_{10} sampler, TSP sampler, TEOM sampler, mass median diameter, under-sampling and over-sampling

Introduction

The National Ambient Air Quality Standards (NAAQS) are the bases for the Environmental Protection Agency (EPA) to regulate the air pollutants including particulate matter (PM) and five other criteria pollutants. Particles with an aerodynamic equivalent diameter (AED) less or equal to 10 micrometers (PM_{10}) and 2.5 μm ($PM_{2.5}$) are currently accepted indicators for PM pollutants. In other words, the regulation of PM is based upon the emission concentration of PM_{10} and $PM_{2.5}$. Industry and researchers question the accuracy of the concentration measurements of PM_{10} and $PM_{2.5}$. The pre-separators of EPA approved PM_{10} and $PM_{2.5}$ samplers are not 100% efficient. As might be expected, there are errors in the measurement of PM_{10} and $PM_{2.5}$. In fact, it has been reported that the use of Federal Reference Method (FRM) PM_{10} and $PM_{2.5}$ samplers to measure emission concentrations of particulate matter having a particle size distribution (PSD) with a mass median diameter (MMD) larger or smaller than 10 μm aerodynamic equivalent diameter results in significant sampling error – over-sampling or under-sampling (Buser et al. 2001, Pargmann et al. 2001).

The PM_{10} inlet (pre-separator) has been used for both EPA approved PM_{10} samplers and for the FRM $PM_{2.5}$ low-volume samplers. The ideal PM_{10} pre-separator (virtual cut) would theoretically remove all particles larger than 10 μm, allowing all particulate matter (PM) less than 10 μm to penetrate to the filter. It is impossible to obtain a virtual cut at 10 μm. Typically, PM_{10} pre-separators are assumed to have performance characteristics (fractional efficiency curve, FEC) that can be described by a lognormal probability distribution with a cut point (d_{50}) and slope. The cut-point is the aerodynamic equivalent diameter of the particle 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 fractional efficiency curve.

The Graseby-Andersen FRM PM_{10} sampler pre-collector was reported to have a d_{50} equal to 10.2 μm and a slope of 1.41 with liquid aerosols (McFarland and Ortiz, 1983). The FRM performance standard for FRM samplers is a cut-point of 10 ± 0.5 μm with a slope of 1.5 ± 0.1 (U. S. EPA 40CFR53, 2000). Buser et al. (2001) reported that PM_{10} measurement errors may be 300 to 500% higher than the correct PM_{10} concentration if the pre-collector operates within the designed FRM performance standards sampling PM with a MMD of 20 μm and geometric standard deviations of 2.0 and 1.5, respectively. Pargmann et al. (2001) reported shifts in cut points of pre-separators exposed to PM larger than the designed cut point. The Graseby-Andersen FRM $PM_{2.5}$ sampler pre-collector - PM_{10} pre-separator needs to be tested for accuracy in the presence of agricultural dusts, which typically have much larger mass median diameters than urban dusts.

The hypotheses of this research were that: (1) the performance characteristics of the PM_{10} pre-separator would change with the change of inlet dust particle size distribution and (2) the measurements of PM_{10} by the PM_{10} sampler would be significantly larger than the "true PM_{10}" in the presence of particle MMD larger than 10 μm. When the MMD of the sampled PM is larger than 10 μm, particles larger than 10 μm will penetrate the PM_{10} pre-separator inlet to the filter and will be measured as PM_{10}. The resulting calculated concentration will be larger than the correct PM_{10} concentration. This result is referred to as over-sampling. If the PM_{10} pre-separators do not monitor agricultural dusts accurately, the fraction of PM_{10} being emitted from cotton gins or from other agricultural operations could suggest that more than the actual mass of PM_{10} is being emitted or present in the ambient air. Research is needed to evaluate the performance characteristics of the PM_{10} pre-separator while sampling agricultural dusts and urban dusts. The first goal of this research was to evaluate the performance characteristics of the PM_{10} pre-separator while sampling agricultural dusts, as well as "simulated" urban dust and also to address the problems that might cause the sampling errors.

There is an alternative way to determine PM_{10} concentration by combining measurements of total suspended particulate (TSP) concentration and PSD of the PM in question. PM_{10} concentration equals

TSP concentration times the mass fraction of PM less than or equal to 10 μm from PSD. The "standard" EPA high-volume TSP sampler operates at a volume flow rate around 85 m^3/hr (50 cubic feet per minute-cfm) (EPA, 1987). It has been observed that the volume flow rate of high-volume TSP samplers was not consistent. In other words, it was difficult to maintain a constant volume flow rate through the high-volume TSP sampler when the filter was heavily loaded. In fact, it is becoming more common practice to measure PM concentration on a low volume basis (Wanjura et al. 2003), which has a volume flow rate of 1 m^3/hr. Wanjura et al. at Texas A&M University (TAMU) designed and built a new low-volume TSP sampler based upon EPA specification of the engineering design parameters for TSP samplers in EPA 40CFR Part 50 (1987). The side-by-side testing results indicated that newly designed TAMU low-volume TSP and EPA "standard" high-volume TSP samplers gave excellent agreement on both TSP concentration and PSD measurements (Wanjura et al. 2003). In this research, TAMU low-volume TSP samplers were used side-by-side with the PM_{10} samplers to evaluate the PM_{10} over sampling problem.

For PM_{10}, and $PM_{2.5}$, the NAAQS are 24-hour concentrations of 150 μg/m^3 and 65 μg/m^3, respectively. It is essential that the duration of any sample measure be 24-hour concentrations. The Tapered Element Oscillation Method (TEOM) sampler is a continuous low-volume sampler, which yields 10-minute, 30-minute, and hourly concentration measurements. The TEOM technology has been approved to be EPA equivalent method for PM measurement. Very few references available in the literature address the accuracy of TEOM sampler measurement of the PM concentration. Another goal of this research was to evaluate the TEOM measurement.

Materials and Methods

Test Materials

In order to evaluate sampling error of PM_{10} inlet and to test the interaction of PM_{10} inlet performance characteristics and PSD of inlet PM, three dusts with different MMD's were used in this laboratory test. Cornstarch was used to represent agricultural dust; fly ash was used to represent industrial dust (i.e. power plant dust) and aluminum oxide, which is the smallest dust we could find, was used to represent "urban" dust. A Coulter Counter Multisizer ™ 3 was used to measure particle size distribution. Cornstarch has a mass median diameter of 19 μm (AED) and geometric standard deviation of 1.4. Fly ash has a mass median diameter of 12 μm and geometric standard deviation of 1.7. Aluminum oxide has a mass median diameter of 8.4 μm and geometric standard deviation of 1.4. The particle densities of each test dust were measured and used to convert the equivalent spherical diameter (ESD) resulting from Coulter Counter particle size distributions to the aerodynamic equivalent diameters by the following equation (Hinds, 1999):

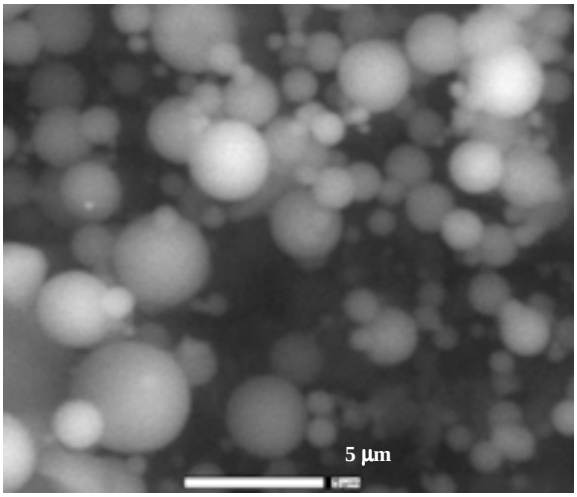
$$AED = ESD * \sqrt{\rho / \chi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where:

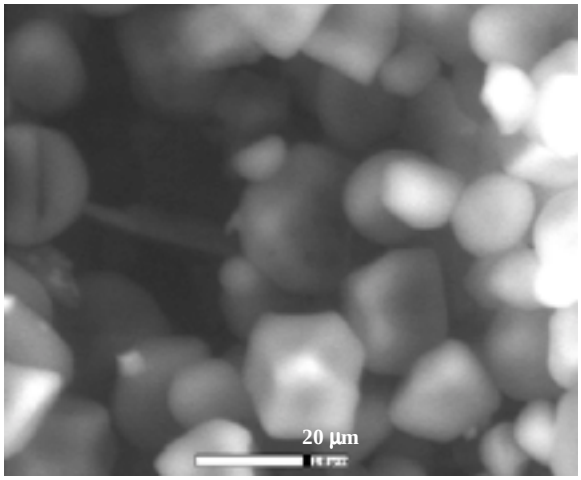
AED = particle aerodynamic equivalent diameter (μm),
ESD = particle equivalent spherical diameter (μm),
ρ = particle density (g/cm^3), and
χ = particle shape factor (χ =1 for spherical particle).

The particle densities for cornstarch, fly ash and aluminum oxide were measured using the AccuPyc1330 pycnometer and were 1.5 g/cm^3, 2.7 g/cm^3 and 3.9 g/cm^3, respectively.

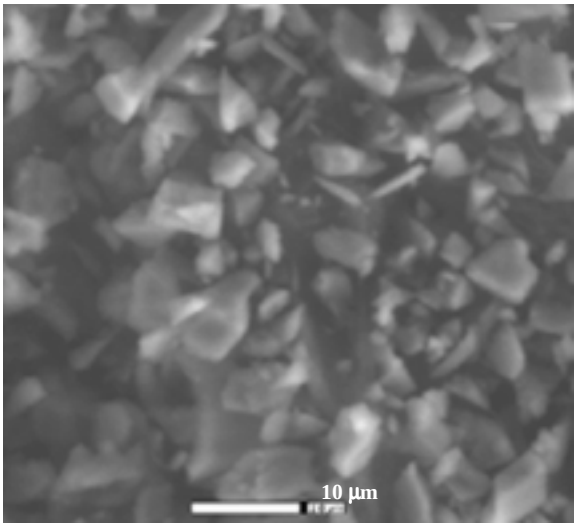
Fly ash, cornstarch and aluminum oxide particles were examined under a scanning electron microscope (SEM). Figure 1 indicates that the fly ash and cornstarch particles are nearly spherical. However the aluminum oxide has particles with angular shape. It has been reported that the shape factor for aluminum oxide particles is 1.44 (Pargmann, 2001).



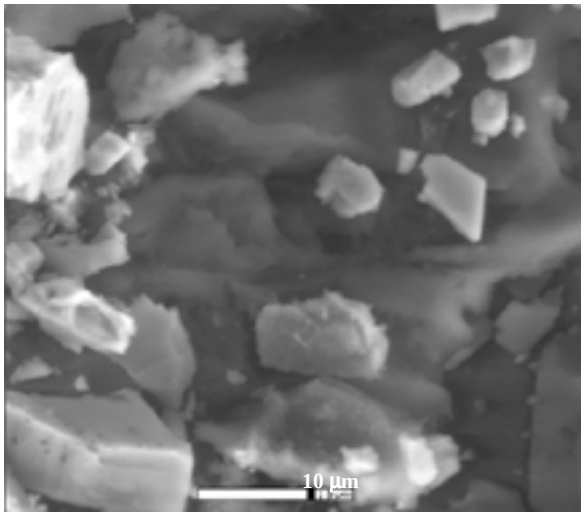
Flay ash particles



Cornstarch particles



Aluminum oxide particles



Dust from oil pipe cleaning system

Figure 1. SEM photos for the dust used in this research

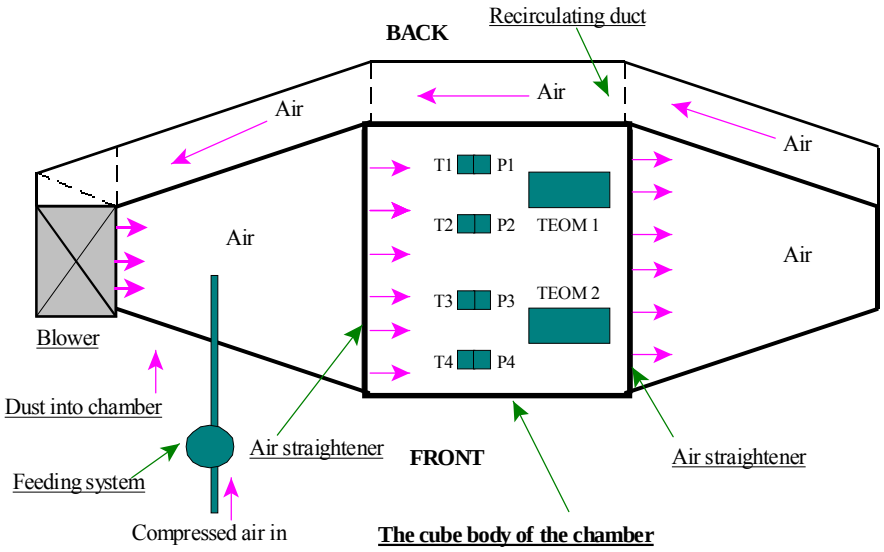
PM_{10} and TSP samplers were also tested side-by-side at an oil pipe cleaning facility site. The dust emitted from the cleaning system has a density of 2.5 g/cm^3, mass median diameter of 8 μm, geometric standard deviation of 2.2. The SEM photo of this dust (Figure 1) shows that it has an irregular shape. It was assumed that this dust has the shape factor of 1.44, the same as aluminum oxide dust.

First Laboratory Tests

Controlled Dust Chamber

Figure 2 shows the top view of the dust chamber used in this research. The dust chamber was initially designed and built for Pargmann's research (2001). It included an external dust feeding system to inject dust into the chamber by compressed air. The chamber consisted of a cubed body portion measuring 2.4 meters 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 m^3/min through the chamber. A duct connected to the opposite transition allowed dust 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 18% open area served as air straighteners located between each transition and the cube body.



T1: low-volume TSP #1 T2: low-volume TSP #2 T3: low-volume TSP #3 T4: low-volume TSP #4
P1: low-volume PM_{10} #1 P2: low-volume PM_{10} #2 P3: low-volume PM_{10} #3 P4: low-volume PM_{10} #4
TEOM 1: TEOM sampler with PM_{10} pre-separator TEOM 2: TEOM sampler with TSP pre-separator

Figure 2. Top view of the dust chamber and sampler setup
(Co-located TSP/PM_{10} testing system)

Samplers and Sampling Systems

Four identical Graseby-Andersen FRM PM_{10} pre-separators, four identical TAMU low-volume TSP samplers and two TEOM samplers (one with TAMU low-volume TSP inlet and one with PM_{10} inlet) were tested side-by-side in the dust chamber (see Figure 2 for the sampler location) in this research (co-locating PM_{10} / TSP tests). Figure 3 shows the vertical locations of the samplers. There was 33cm (13 inch) height difference between PM_{10} samplers' inlets and TSP samplers' inlets. The height of TEOM/TSP inlet was the same as PM_{10} samplers' inlets. It was assumed that the dust concentration in the chamber is constant due to air mixing in the first 45° transition part of the chamber before passing into the cube body. Another purpose of setting four TSP samplers side-by-side along the perforated wall was to test this assumption.

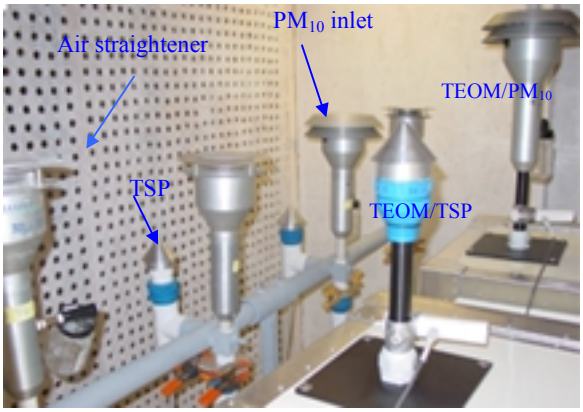


Figure 3. View of the sampler location inside the dust chamber and air straightener

Five tests were conducted for each dust with one-hour duration of each test. The chamber was carefully cleaned before new dust was introduced. Because of heavy loading, the impaction surfaces of PM_{10} inlets were cleaned for each run to minimize the sampling error caused by the possible dust carry-over.

Figures 4&5 show the TSP and PM_{10} sampling system. An orifice meter, pressure transducer and an adjustable needle valve were used in the system to monitor and maintain a constant airflow rate during the one-hour testing time. The proper flow rate through PM_{10} pre-separators and low-volume TSP samplers is one cubic meter per hour (1 m^3/hr).

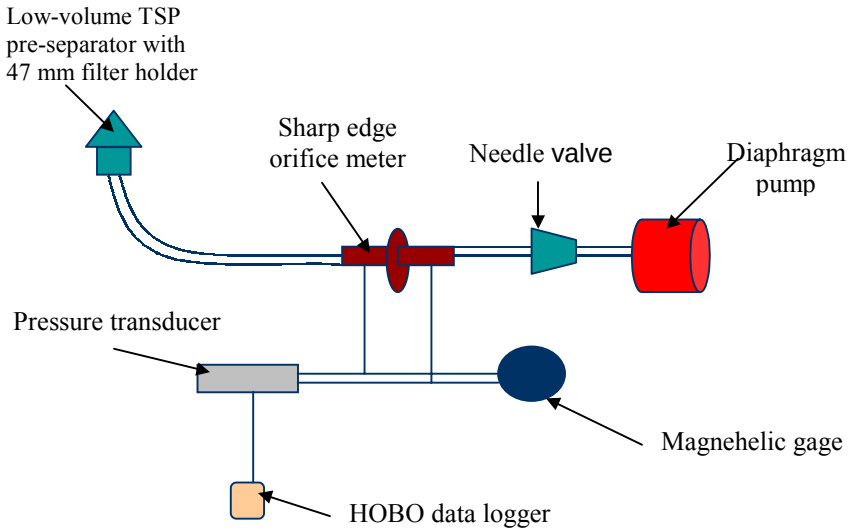


Figure 4. Low-volume TSP sampling system

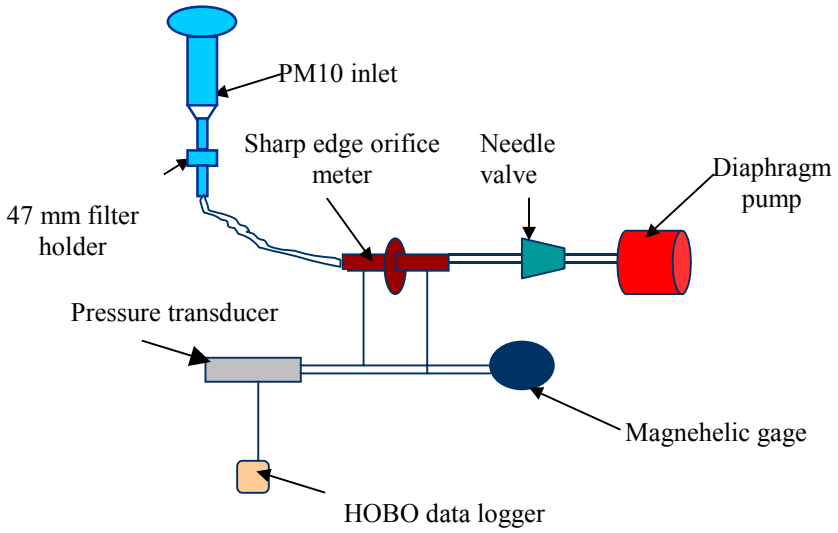


Figure 5. Low-volume PM_{10} sampling system

In the low-volume TSP and PM_{10} pre-separator sampling systems, the pump pulled the dusty air through a TSP / PM_{10} inlets to a Teflon filter. The PM, which penetrated the TSP / PM_{10} inlet, was captured on the filter, and the clean air was pulled by a pump and 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.

$$Q = 3.478 * K * D_o^2 * \sqrt{\Delta P / \rho_a} \quad \text{.....(2)}$$

where,

Q = air flow rate through the orifice meter (m^3/s),
K = flow coefficient (dimensionless),
D_o = orifice diameter (m),
ΔP = pressure drop cross the orifice (mm H_2O), and
ρ_a = air density (kg/m^3).

A HOBO data logger and a pressure transducer were used for each system to record the pressure drop across the orifice every 12 seconds during the one hour testing period for each trial. Using this pressure drop, the flow rates pulled through the filter (system) were calculated for every 12 seconds by equation 2. This flow rate was used to calculate the total volume of air through the system during the one-hour testing period and subsequently to calculate the dust concentration that penetrated the sampler pre-separator.

Forty-seven millimeter (47 mm) disks PTFE Teflon filters were used for PM_{10} inlet and TSP sampler testing. The filters were placed in plastic petri dishes to prevent handling contamination. Concentration and PSD measurements from TSP samplers were used to determine the dust concentration and PSD in the chamber at their respective location for each test.

Second Laboratory Tests

After first set of laboratory tests, it was observed that the dust concentration distributions in the chamber were not uniform in the front half of the chamber. The dust feeding system was modified (shown in Figure 6) to adjust the concentration distribution in the chamber; meanwhile TSP samplers were raised to the same height as PM_{10} samplers. Three more tests with fly ash were run to evaluate this adjustment.

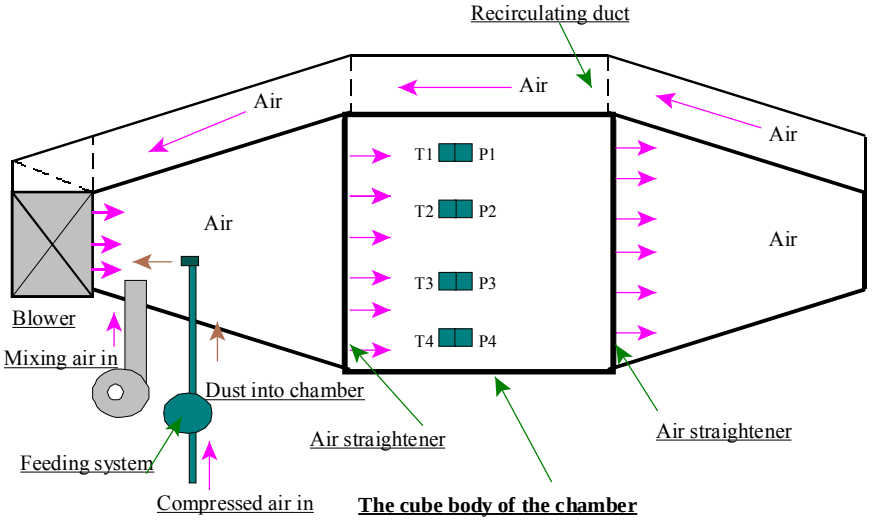


Figure 6. Top view of the dust chamber with modified dust-feeding system

Field Sampling

Field tests were conducted in collaboration with the Nuclear Engineering Department at Texas A&M University (TAMU). The sampling source came from 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 oil pipe to clean the inside surface of the pipe. Dust was emitted from the end of the pipe. At the same time as the pipe inside surface was being cleaned, a medal brush was cleaning the outside surface of the pipe. Two cyclones were used to collect the rusty dust from the outside surface of the pipe. Four PM_{10} and four TSP samplers were placed side-by-side at 1, 2, and 3 meters from the pipe as shown in the Figures 7 and 8.

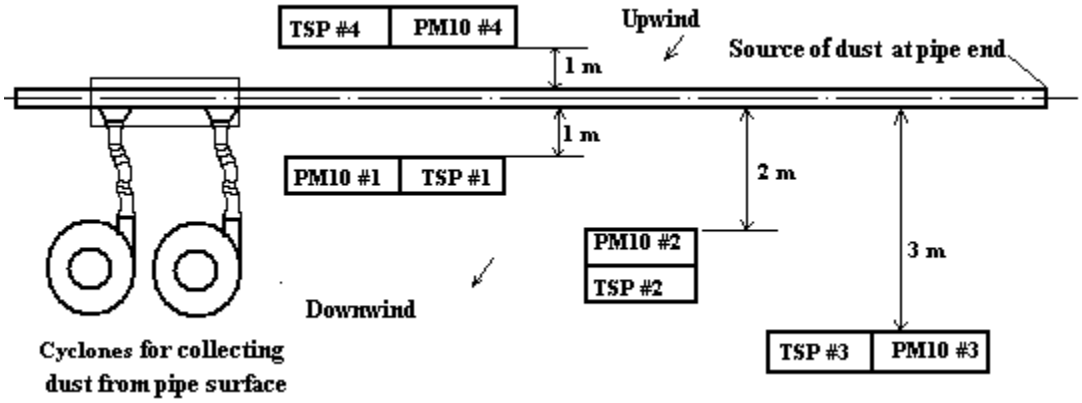


Figure 7. Top view of the oil pipe cleaning system and PM sampler location

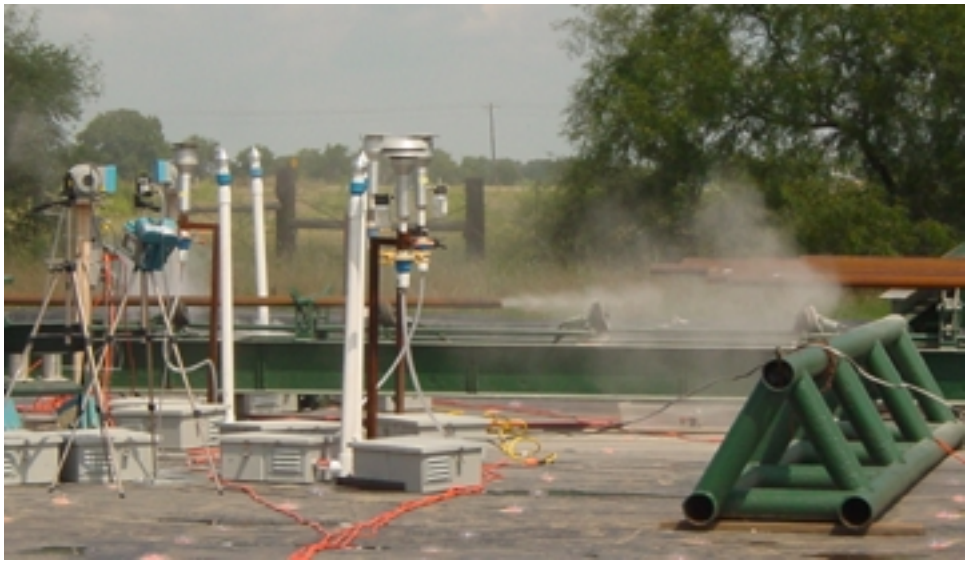


Figure 8. View of dust plume from oil pipe

TSP and PM_{10} Concentration Calculations

TSP and PM_{10} concentrations were determined by dividing the mass captured on the filter by the total volume of air through the sampler during the one-hour sampling period. Pressure drop readings were used

to calculate a volume flow for the 12-second intervals. The following equation was used for calculation of the concentrations.

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

where,

Con. = one hour concentration (mg/m^3),
M = mass captured on the filter (mg),
Q = 12 second air flow rate through the orifice meter (m^3/s), and
t = time interval for the HOBO to read the measurement data through pressure transducer (12 seconds).

PM_{10} Inlet Fractional Efficiency Curve Calculation

A fractional efficiency curve is a description of the percent mass captured versus particle size. Four parameters were obtained to develop PM_{10} sampler's fractional efficiency curve. These parameters were:

1. Inlet dust concentration - measured dust concentrations by the TSP sampler,
2. Inlet particle size distribution (PSD) - PSD of PM sampled by the TSP sampler,
3. Emission concentration - measured dust concentrations in the chamber by the PM_{10} samplers, and
4. Outlet PSD of PM captured on the PM_{10} filters.

The inlet and outlet concentrations for various size ranges were calculated using inlet and outlet dust concentrations and the 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 one with the resulting values being the fractional efficiencies for each size range as shown in the equation 4.

$$\eta_j = (1 - C_{oj} / C_{ij}) \quad \text{..... (4)}$$

where:

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

The fractional efficiency curve is most commonly represented by a lognormal distribution with a cut–point and a slope. The cut-point is the particle size where 50% of PM is captured and 50% penetrate to the filter. The slope is the ratio of the 84.1% and 50% particle size or the ratio of the 50% and 15.9% particle size from the fractional efficiency curve.

Over Sampling Rate Calculation

It has been reported that there is an inherent sampling bias associated with PM_{10} sampler (Buser et al. 2001). Over sampling will occur when a PM_{10} sampler exposes to the dust with MMD larger than 10 μm. The over sampling rate of the PM_{10} sampler is determined by the following equation:

$$\varepsilon = 100 * (R_m - R_t) / R_t \quad \text{..... (5)}$$

where:

ε = over sampling rate (%),
R_m = measured PM_{10} / TSP ratio, and
R_t = true PM_{10} / TSP ratio.

Besides the over-sampling problem associated with the PM_{10} sampler, the under-sampling problem will occur when a PM_{10} sampler is used with dust MMD smaller than 10 μm (Buser et al. 2001). The same equation (5) can be used to evaluate the under-sampling rate.

Results and Discussion

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 test was conducted for one-hour period. Standard analysis of variance (ANOVA) tests were conducted to determine the statistical difference among the samplers by Tukey's Studentized Range (HSD) test at 95% confidence interval.

First Laboratory Test results

PM Concentration Measurement

Table 1 lists the resulting PM concentration measurement from the first set of laboratory tests utilizing the PM_{10}, TSP and TEOM samplers. There were considerable variations in the concentrations measured by four identical TSP samplers. The significant difference between TSP measurements indicates that there was a horizontal concentration gradient across the chamber along the perforated wall direction. However, the concentration difference between T3 and T4 is not significant. It suggests that the concentration in the front half of the chamber (see Figure 2 for front-side definition) was horizontally constant.

Table 1. Measured one-hour concentration (mg/m^3)

		PM_{10}					TSP				
Dust	Test #	P1	P2	P3	P4	TEOM 1	T1	T2	T3	T4	TEOM 2
CS	1	15	20	18	15	17	22	10	46	42	42
CS	2	19	25	22	19	18	32	54	73	63	56
CS	3	10	13	13	11	7	14	25	38	32	29
CS	4	12	14	12	13	6	16	29	44	39	30
CS	5	7	9	8	8	4	10	17	26	31	21
AO	6	19	24	22	19	3	12	21	25	22	21
AO	7	28	31	34	30	3	18	30	38	33	33
AO	8	33	41	40	35	5	17	38	45	39	45
AO	9	39	49	45	41	7	26	42	52	46	52
AO	10	35	47	40	34	6	21	37	47	42	49
FA	11	52	66	55	50	12	38	68	62	67	63
FA	12	39	46	35	36	11	24	46	45	42	50
FA	13	34	45	35	33	11	27	41	42	41	45
FA	14	24	33	26	23	7	19	30	29	28	31
FA	15	25	32	25	24	9	17	29	30	29	33

- P1 - P4 are the PM_{10} samplers. T1 - T4 are the low-volume TSP samplers
- TEOM1 is the tapered element oscillation method sampler with PM_{10} inlet
- TEOM1 is the tapered element oscillation method sampler with TSP inlet

- CS is cornstarch; AO is aluminum oxide; and FA is fly ash.

In the back half of the chamber, the PM_{10} measurements are higher than TSP measurements for Aluminum oxide and fly ash dusts (see co-located P1 &T1, P2 &T2). The PM_{10} measurement cannot be higher than the TSP measurement if both samplers were exposed to the PM at the same concentration. Only reason that the PM_{10} measurements could be higher than the TSP measurements from two co-located samplers could be that there was a vertical concentration gradient in the chamber. In fact, there was a 33 cm (13 inch) height difference between the PM_{10} inlet and TSP inlet. It was also observed that the dust was injected into the chamber through a plastic tube by the compressed air. The outlet end of the tube was located between sampler T2 and T3 and was pointing upward. It is assumed that the compressed air was not well mixed with the airflow in the chamber. This caused a dust plume towards the backside of the chamber and upward. As a result, the dust in the back half of chamber was not uniformly distributed. It generated a concentration gradient in both the horizontal direction and the vertical direction in this half of the chamber. On the other hand, in the front half of the chamber, there was no compressed air impacting on the dust plume. The dust concentrations are constant (see T3 and T4 measurements). TEOM 2 located between T3 and T4 is a TSP sampler with the TSP inlet at the same height as PM_{10} inlet. The concentration measured by TEOM2 is not significantly different from T3 and T4. This indicates that there is no vertical concentration gradient in the front half of the chamber. All these observations suggest that the dust chamber used in this research was a semi-constant concentration dust chamber which means that dust 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 P3/T3, P4/T4 samplers were used for PM_{10} characteristics analyses.

Since a concentration gradient existed (horizontally and vertically) in the back half of the chamber, there is no comparison of PM_{10} measurements between PM_{10} sampler and TEOM/PM_{10} sampler. However, in the front half of the chamber, TEOM/TSP (TEOM1) yielded excellent agreement measurement with TSP samplers. This indicates that the TEOM sampler gave excellent one-hour concentration measurements in the laboratory conditions.

PM_{10} / TSP Ratio Measurements and Over-Sampling Rates

Tables 2 and 3 list the PM_{10}/TSP ratio measurements and the average over sampling rate for comparison. The average of PM_{10} fractions of TSP using PM_{10}/TSP ratio from co-located P3/T3 and P4/T4 samplers are 32%, 83% and 88% for corn starch, fly ash and aluminum oxide, respectively. Comparing these ratios to the average fractions obtained from Coulter Counter PSD's of PM from TSP samplers (considered as true PM_{10} fraction), we have average PM_{10} fractions (from TSP samplers) of 17%, 59% and 77% for cornstarch, fly ash and aluminum oxide, respectively. The comparison of the PM_{10} samplers' PM_{10}/TSP ratios and PM_{10} fraction from TSP sampler measurements indicated the over-sampling of PM_{10} samplers. The PM_{10} sampler over-sampling rates increase with the increase of MMD (see table 3 for MMD of PM in the chamber).

Table 2. Comparison of PM_{10}/TSP ratio measured by the PM_{10} and TSP samplers and the true PM_{10}/TSP ratio (PM_{10} fraction) obtained from PSD's of TSP samplers

Dust	Test #	Con. from P3	Con. from T3	Measured PM_{10} / TSP	True PM_{10} / TSP	Con. from P4	Con. from T4	Measured PM_{10} / TSP	True PM_{10} / TSP
CS	1	18	46	39%	22%	15	42	36%	25%
CS	2	22	73	30%	18%	19	63	30%	16%
CS	3	13	38	34%	12%	11	32	34%	13%
CS	4	12	44	27%	12%	13	39	33%	19%
CS	5	8	26	31%	15%	8	31	26%	15%

Average				**32%[a]**	**16%[b]**			**32%[a]**	**18%[b]**
AO	6	22	25	88%	58%	19	22	86%	63%
AO	7	34	38	89%	80%	30	33	91%	80%
AO	8	40	45	89%	84%	35	39	90%	79%
AO	9	45	52	87%	85%	41	46	89%	80%
AO	10	40	47	85%	76%	34	42	81%	82%
Average				**88%[c]**	**77%[d]**			**87%[c]**	**77%[d]**
FA	11	55	62	89%	48%	50	67	75%	51%
FA	12	35	45	78%	51%	36	42	86%	62%
FA	13	35	42	83%	66%	33	41	80%	65%
FA	14	26	29	90%	57%	23	28	82%	61%
FA	15	25	30	83%	68%	24	29	83%	64%
Average				**85%[c]**	**58%[d]**			**81%[c]**	**60%[d]**

- CS is cornstarch; AO is aluminum oxide; and FA is fly ash.
- P3 & T3 are co-located PM_{10} and TSP samplers; P4 & T4 are co-located PM_{10} and TSP samplers.
- Con. = measured concentration (mg/m^3)
- Measured PM_{10}/TSP ratio is the ratio of measured PM_{10} and TSP concentration by the respective samplers
- True PM_{10}/TSP ratio is the PM_{10} fraction of PSD from TSP sampler measurement
- Means with the same letter are not significantly different at 0.05 levels.

Table 3. Average over-sampling rate (%) measured by two PM_{10} samplers

	MMD (μm)	PM_{10} sampler #3	PM_{10} sampler #4
Cornstarch	16	100%	78%
Fly ash	11	46%	35%
Aluminum oxide	11	14%	14%

- MMD is the average mass median diameter (AED) of PSD on the TSP sampler filters; it is not the MMD of the original dust.

Cut-points and Slopes of PM_{10} inlets

Based on the inlet concentrations & PSD (measured by TSP sampler) and outlet concentration & PSD (measured by PM_{10} sampler), the fractional efficiency curves of PM_{10} inlets were calculated by using equation 4. Cut-points and slopes were determined from the fractional efficiency curves. Table 4 shows the resulting PM_{10} inlet cut-points and slopes for each dust. Cut-points larger than 10 μm indicate the over-sampling problem. The statistical analysis indicates that the average cut-points and slopes of P3/P4 are not significantly different for cornstarch, fly ash and aluminum oxide. The calculated data indicate that the cut-point increased with a decrease of MMD of PM.

It should be emphasized that a shift in cut-point away from the range of 10 ± 0.5 μm (AED) will significantly increase the measurement errors. None of the cut-points for these three dusts are in this range. Therefore, the over-sampling problems were observed.

Table 4. PM_{10} inlets cut-points (μm) and slopes

		P3		P4	
Dust	Test #	Cut-point (μm)	Slope	Cut-point (μm)	Slope
CS	1	12.5	1.3	12.0	1.3
CS	2	11.5	1.4	12.5	1.3
CS	3	13.2	1.3	13.2	1.3
Average		**12.4[a]**	**1.3**	**12.6[a]**	**1.3**
AO	6	18.0	1.4	16.0	1.4
AO	7	17.0	1.5	17.0	1.5
AO	8	18.0	1.5	16.0	1.6
Average		**17.6[b]**	**1.5**	**16.3[b]**	**1.5**
FA	11	17.5	1.3	18.5	1.3
FA	12	17.0	1.5	19.0	1.6
FA	13	17.0	1.5	17.0	1.5
Average		**17.2[b]**	**1.4**	**18.2[b]**	**1.5**

- CS is cornstarch; AO is aluminum oxide; and FA is fly ash
- P3 & P4 are PM_{10} samplers
- Cut-points and slopes were obtained from fractional efficiency curves, which were calculated using inlet and outlet concentration and PSD's (equation 4). For P3 sampler, inlet concentration and PSD were obtained from its co-located TSP sampler's (T3) measurements, whereas, P4 sampler, inlet concentration and PSD were obtained from its co-located TSP sampler's (T4) measurements.
- Means with the same letter are not significantly different at 0.05 levels.

Second Laboratory Test Results

The second laboratory test results are listed in the table 5. Four TSP (T1, T2, T3 and T4) samplers' concentration measurements are not statistically different. This indicates that the modified dust feeding system produced a uniform concentration in the chamber. However, there are significant differences among four PM_{10} sampler (P1, P2, P3 and P4) measurements. As a result, the over-sampling rates among four PM_{10} samplers are significant different. The performance standard of a cut-point of 10 ± 0.5 μm with a slope of 1.5 ± 0.1 (U. S. EPA 40CFR53, 2000) for PM_{10} sampler indicates that for the different PM_{10} samplers, their cut-points and slopes could be different from one to the other in a certain range. It was this difference that caused the different PM_{10} measurement among P1, P2, P3 and P4 samplers. The results in table 5 also indicate that the over-sampling rates vary with the change of the dust loading (concentrations measured by TSP samplers for different tests).

Table 5. Second laboratory test results with fly ash dust: measured one-hour concentration (mg/m^3), PM_{10}/TSP ratio and over-sampling rate

Test #	Con. from P1	Con. from T1	Measured PM_{10}/TSP	True PM_{10}/TSP	Over-sampling rate	Con. from P2	Con. from T2	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 %

Average			**78 %**		**20 %**			**95 %**		**50 %**
Test #	Con. from P3	Con. from T3	Measured PM_{10}/TSP	True PM_{10}/TSP	Over-sampling rate	Con. from P4	Con. from T4	Measured PM_{10}/TSP	True PM_{10}/TSP	Over-sampling rate
1	26	32	81 %	67 %	21 %	---	---	---	---	---
2	19	26	73 %	65 %	12 %	18	25	72 %	59 %	22 %
3	21	30	70 %	---*	---	20	30	67 %	55 %	22 %
Average			**75 %**		**17 %**			**83 %**		**22 %**

- P1 / T1, P2 / T2, P3 / T3, and P4 / T4 are co-located PM_{10} and TSP samplers (see Figures 2 & 6 for sampler location).
- Con. = measured concentration (mg/m^3).
- Measured PM_{10}/TSP ratio is the ratio of measured PM_{10} and TSP concentration by the respective samplers.
- True PM_{10}/TSP ratio is the PM_{10} fraction of PSD from TSP sampler measurement.
- Over-sampling rates were determined by equation 5.
- *: No PSD measurement because the filter was used for SEM photo analysis.

Field Sampling Results

The field sampling results are included in the tables 6 & 7. As Figure 7 shows, TSP # 1, 2, 3 were located at downwind and TSP #4 was located at upwind. There was a concentration difference in the space because the PM dispersion caused by wind (see TSP #1, 2, 3, and 4 measurements). The results from co-located TSP and PM_{10} samplers were used to evaluate the PM_{10} samplers. It is observed that the MMD of PM on the TSP filters are different with the different locations (table 7). The dust concentration on the upwind sampler filter is too low to make a PSD measurement. The MMD's of the dust from the oil pipe cleaning system are smaller than 10 μm (table 7); as a result, an under-sampling problem occurred. In fact, the negative over-sampling rates in the table 6 suggest the under-sampling problem. The under-sampling rate also changed with the change of the dust loading (TSP concentration).

Table 6. Field-testing results with the dust emitted from an oil pipe cleaning system: measured concentration (mg/m^3), PM_{10}/TSP ratio and over-sampling rate

Testing time	Con. from PM_{10} # 1	Con. from TSP # 1	Measured PM_{10}/TSP	True PM_{10}/TSP	Over-sampling rate	Con. from PM_{10} # 2	Con. from TSP # 2	Measured PM_{10}/TSP	True PM_{10}/TSP	Over-sampling rate
06/16/03	2.8	12.7	22 %	81 %	- 73 %	5.1	12.9	39 %	84 %	- 54 %
06/17/03	2.2	8.1	27 %	52 %	- 48 %	2.7	11.5	23 %	79 %	- 71 %
Average			**25 %**		**- 61 %**			**31 %**		**- 63 %**
Testing time	Con. from PM_{10} # 3	Con. from TSP # 3	Measured PM_{10}/TSP	True PM_{10}/TSP	Over-sampling rate	Con. from PM_{10} # 4	Con. from TSP # 4	Measured PM_{10}/TSP	True PM_{10}/TSP	Over-sampling rate
06/16/03	--- *	1.6	--- *	76 %	--- *	0.27	0.35	77 %	--- **	--- **
06/17/03	1.6	5.8	28 %	62 %	- 55 %	0.26	0.57	46 %	--- **	--- **
Average			**28 %**		**- 55 %**			**62 %**		---

- PM_{10} #1 / TSP #1, PM_{10} #2 / TSP #2, PM_{10} #3 / TSP #3, and PM_{10} #4 / TSP #4 are co-located PM_{10} and TSP samplers (see Figure 8 for sampler location: PM_{10} #4 / TSP #4 were located at upwind; whereas PM_{10} #1 / TSP #1, PM_{10} #2 / TSP #2, and PM_{10} #3 / TSP #3 were located at downwind).
- Con. = measured concentration (mg/m^3).

- Measured PM_{10}/TSP ratio is the ratio of measured PM_{10} and TSP concentration by the respective samplers.
- True PM_{10}/TSP ratio is the PM_{10} fraction of PSD from TSP sampler measurement.
- Over-sampling rates were determined by equation 5, negative over-sampling rate indicates under-sampling problem.
- *: No PM_{10} measurement.
- **: Not enough dust on the filter to run Coulter Counter for PSD measurements.

Table 7. Measured PSD of the dust in the testing field

Testing	Measured by TSP #1		Measured by TSP #2		Measured by TSP#3		Measured by TSP #4	
time	MMD (μm)	GSD	MMD (μm)	GSD	MMD (μm)	GSD	MMD (μm)	GSD
06/16/03	5.9	1.7	5.5	1.7	6.1	1.9	---*	---*
06/17/03	9.6	2.4	6.3	1.8	8.0	2.2	---*	---*

- TSP #1, TSP #2, TSP #3, and TSP #4 are TSP samplers (see Figure 8 for sampler location).
- MMD is the mass median diameter (AED) of PSD on the TSP sampler filter.
- GSD is the geometric standard deviation of PSD on the TSP filter.
- *: Not enough dust on the filter to run Coulter Counter for PSD measurements.

Conclusions

The following conclusions were made based on the results of this study:

1. The dust chamber with modified feeding system used in this research produced a uniform dust concentration distribution. It is excellent facility for side-by-side air sampling tests.
2. The experimental test results in this research demonstrate that PM_{10} samplers over-sample when exposed to ambient PM having MMD's larger than 10 micrometers AED, whereas PM_{10} samplers under-sample when exposed to ambient PM having MMD's smaller than 10 micrometer AED.
3. Over-sampling rates by PM_{10} samplers increase with the increase of the MMD of inlet PM whereas the under-sampling rate increase with the decrease of MMD. In other words, the further away from 10 μm the MMD, the higher over-sampling / under-sampling rates the PM_{10} sampler will have.
4. Over-sampling / under-sampling rates change with change of the dust loading (TSP concentration).
5. The cut-points and slopes of the PM_{10} pre-separator changed with the change of MMD's of inlet PM.
6. The fractional efficiency curve shifted to the right with the decrease of the MMD of the inlet PM. This is a different conclusion than reported by Pargmann et al. (2001).
7. TEOM/TSP (TEOM1) yielded excellent agreement measurement with TSP samplers.

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