EVALUATION OF PM_{10} PRE-SEPARATOR FOR LOW-VOLUME SAMPLING

Lingjuan Wang, John D. Wanjura,Todd E. Stiggins, Graduate Research Assistants
Calvin B Parnell, Jr. Ph. D., P.E., Regents Professor
Ronald E. Lacy, Ph. D., P.E., Associate Professor
Bryan W. Shaw, Ph. D., Associate Professor
Department of Biological & Agricultural Engineering
Texas A&M University
College Station, TX

Abstract

Two identical PM_{10} pre-separators, along with two identical low-volume ($1 m^3$/hr) total suspended particulate (TSP) samplers and two identical high-volume ($85 m^3$/hr) TSP samplers were tested side-by-side in a controlled laboratory dust chamber. The test results show that PM_{10} samplers over-sample when exposed to ambient PM having mass median diameters (MMD's) larger than 10 micrometers aerodynamic equivalent diameter (AED). The cut-points and slopes of PM_{10} pre-separator changed with the change of MMD's of inlet particulate matter (PM). The fractional efficiency curve shifted to the right with the decrease of the MMD of the inlet PM. Analysis of the results suggest that co-locating PM_{10} and TSP samplers may offer a process that can be used to correct for PM_{10} sampler error.

Introduction

The PM_{10} pre-separator has been used for both EPA approved PM_{10} samplers and for the Federal Reference Method (FRM) $PM_{2.5}$ low-volume sampler. 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) that can be described by a lognormal probability distribution with a cut point (d_{50}) and a slope. The cut-point is the aerodynamic equivalent diameter (AED) 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 10.2μm (AED) 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. Environmental Protection Agency 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 mass median diameter (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 has not been tested for accuracy in the presence of agricultural dusts, which 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 will change with the inlet dust particle size distribution and (2) the measurements of PM_{10} would be significantly larger than the "true PM_{10}". 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 a large than 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 goal of this research was to evaluate the performance characteristics of the PM_{10} pre-separator while sampling agriculture dusts, as well as "simulated" urban dust and also to address the problems that might cause the sampling errors.

Materials and Methods

Test Materials

Cornstarch, fly ash and aluminum oxide were used in this research. Cornstarch was used to represent agriculture dust. A Coulter Counter Multisizer^{TM}3 was used to determine particle size distribution of the particulate matter (PM). Cornstarch has a mass median diameter of 19 μm (AED) and geometric standard deviation of 1.4. Fly ash has a mess median diameter of 13 μm and geometric standard deviation of 2.4. Aluminum oxide has a mess median diameter of 9 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 (PSD) to the aerodynamic equivalent diameters (AED) by the following equation (McFarland et al, 1978):

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

where:

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

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.

Dust Chamber and Feeding System

A dust chamber was initially designed and built for Pargmann's research (2001). This chamber included an external dust feeding system. The chamber (see Figure 1) 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 were located between each transition and the cube body. (see Figure 2).

The external dust feeding system was adapted from Pargmann's research (2001). This dust feeder was used to inject dust into the chamber. A venturi feeder was used to move the test dust from a radial rectangular groove in an aluminum disk with into the chamber through a plastic tube. The suction side of the venturi tube was located above the groove. Air passed through the venturi tube, the disk turned, dust was moved into the system and was conveyed into the chamber through the plastic tube (see Figure 3). The motor speed was set to turn the dust-feeding disk at four revolutions per hour for cornstarch, 1.5 revolutions per hour for fly ash and 1 revolution per hour for aluminum oxide.

Samplers

Two identical Graseby-Andersen FRM PM_{10} samplers with associated pre-separators (P1&P2) were tested in this study. Two identical high volume total suspended particulate (HTSP) samplers (HT1&HT3) were also used. One HTSP sampler (HT3) was used with glass fiber filters to determine the concentration of the dust present in the dust chamber for each test. The other HTSP sampler (HT1) was operated with polyweb filters to obtain the particle size distribution (PSD) of PM in the chamber. Two low-volume total suspended particulate (LTSP) samplers (T1&T2) were also tested side-by-side with two PM_{10} pre-separators to compare the PM_{10} measurements. There was another modified HTSP sampler (HT2) tested simultaneously in the chamber for another research (Boriack, 2003). Figure 4 shows PM_{10} pre-separator sampling system. The TSP sampling systems are similar to the PM_{10} sampling system. An orifice meter, pressure transducer, and an adjustable valve were used in the system to monitor and keep the airflow rate through the system constant. The proper flow rates through PM_{10} pre-separators and LTSP samplers are one cubic meter per hour (1 m^3/hr), whereas the proper flow rates through HTSP samplers are eighty-five cubic meters per hour (85 m^3/hr).

In the PM_{10} pre-separator sampling system, the pump pulled the dusty air through a PM_{10} inlet to a Teflon filter. The PM, which penetrated the 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 cross the orifice meter. The following equation was used to set the proper pressure drop across the orifice meter.

$$Q = 5.976 * K * D_o^2 * \sqrt{\frac{\Delta P}{\rho}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

where,

Q = air flow rate through the orifice meter (cfm),
K = flow coefficients (dimensionless),
D_o = orifice diameter (inch),
ΔP = pressure drop cross the orifice (in H_2O), and
ρ = air density (lb/ft^3).

With the increase of collecting dust on the filter, the system flow rate decreased. A *Cole-Parmer Valved Acrylic Flowmeter* (A-32460-48) was used in the system as an adjustable valve to maintain the flow rate at the design level (16.67 L/min). 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. Concentration was determined by dividing the mass on the filter by the total volume of air through the sampler during the sampling period.

Forty-seven millimeter (47 mm) disks, supported PTFE Teflon filters used for PM_{10} inlet and LTSP sampler testing. The filters were placed in plastic petri dishes to prevent handling contamination. Polyweb filters (20.3 cm x 25.4 cm) were used for one HTSP (see Figure 1, HT1) to determine the dust PSD in the chamber for each test. Glass fiber filters (20.3 cm x 25.4 cm) were used for high-volume TSP sampling (HTP3) to determine the dust concentration in the chamber for each test. All the filters were conditioned in an environmental chamber for at lease 24 hours before they were weighed. The environmental chamber was controlled to maintain temperature at 20-30 ^{o}C and relative humidity at 30-40%, as specified by EPA. The filter pre- and post-weights were measured with a microbalance located in the environmental chamber. The difference between the filter's pre-weight ant the post –weight yielded the mass captured on the filter during the test period.

PM_{10} Pre-separator Fractional Efficiency Curve

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 - This was the measured dust concentrations in the chamber by the HTSP sampler (HT3-Figure 1).
2. Inlet particle size distribution (PSD) - This was the PSD of PM in the chamber, sampled by the other HTSP sampler (HT1- Figure 1).
3. Emission concentration - This was the measured dust concentrations in the chamber by the PM_{10} samplers.
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 3.

$$\eta_j = (1 - C_{oj} / C_{ij}) \quad \text{………………………………………} \quad (3)$$

where:

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

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 15 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.

Concentrations

Table 1 lists the resulting PM concentration measurements utilizing the PM_{10} and TSP samplers. There were considerable variations in the concentrations reported using the two PM_{10} samplers (P1&P2), whereas the two low-volume TSP samplers (T1&T2) consistently yielded the same concentration measurement for all tests. The concentrations measured with high volume TSP sampler were not as consistent as the two low-volume TSP samplers' measurements for the different test conditions. There were heavy PM loadings on the filters of the high-volume TSP samplers on a number of the tests. These heavy filter loadings caused resulted in increases in pressure drop across the filters, and subsequent changes of flow rates for these particular tests. As a result of the fluctuation of system airflow rates, the measurements of the high-volume TSP concentrations were not as consistent as the low-volume TSP concentration measurements. Flow rates for the low-volume TSP sampler systems were relatively constant for all test conditions. As a consequence, the resulting low-volume TSP samplers yielded more reliable TSP concentration measurements.

One interesting observation was that concentrations using the P1 samplers were significantly higher than P1 measurements for all but 1 test, whereas T1 and T2 measurements were the same. (Samplers P1&P2 were identical and samplers T1&T2 were identical.) The test conditions for samplers P1, P2, T1 and T2 were identical for all tests. (See figure 1.). T1&T2 were located at the two sides of the chamber, and P1&P2 were set near the middle. Dust was introduced to the middle of the chamber prior to the first air straightener. It was assumed that there would be a slight concentration gradient across the dust chamber center. The resulting 1-hour average concentrations determined with T1and T2 samplers (see table 1) would suggest that this assumption was incorrect. PM_{10} samplers with their associated pre-separators are very sensitive to the ambient PM concentrations in the size range near the designed cut point of the pre-separator. TSP samplers are not sensitive to variations in concentrations near the PM_{10} pre-separators cut point. One explanation of the large variation in measured PM_{10} concentrations is that slight variations of PM concentrations near the designed cut point of the pre-separator could have cause significant differences of concentration measurements by the two side-by-side FRM PM_{10} samplers. At the same time, the low-volume TSP samplers would not have detected the variations of PM in this size range.

Table 2 lists the PM_{10} concentration measurements from PM_{10} samplers and from TSP samplers. The PM_{10} concentrations measured by TSP samplers were obtained by using measured TSP concentration times the fraction of the PM less than 10 μm AED from PSDs on the filters of TSP sampler. Results in the table 2 show that PM_{10} concentrations measured by PM_{10} samplers (P1&P2) are always higher than the PM_{10} concentration calculated from TSP measurements. This indicates over-sample problems by PM_{10} samplers for all three kinds of dust. The calculations of (PM_{10}/TSP) ratios are also listed in the table 2 for comparison. Since the low-volume TSP sampler had more consistent measurements, TSP concentrations measured by the T1 sampler were used to calculate (PM_{10}/TSP) ratio measured by the P1& P2 samplers. The average PM_{10} fractions of TSP using (PM_{10}/TSP) ratios from P1&P2 samplers are approximately 45%, 64% and 80% for corn starch, fly ash and aluminum oxide, respectively. Comparing these ratios to the fraction obtained from Coulter Counter PSD's, we get average fractions (from T1&HT1 samplers) of 27%, 40%, and 50% for cornstarch, fly ash and aluminum oxide, respectively. The comparison of the PM_{10} sampler's (PM_{10}/TSP) ratios and PM_{10} fraction from TSP sampler measurements also indicated the over-sampling of the PM_{10} samplers. The PM_{10} sampler measurement errors increase with the decrease of the MMD of inlet PM. It seems that the over-sampling of the PM_{10} samplers results in a PM_{10}/TSP ratio that is approximately 20% higher than the true value (from TSP sampler). It may be possible to correct for over-sampling by analyzing results from side-by-side PM_{10} and TSP sampling.

Cut-points & Slopes of PM_{10} Pre-separators

Based on the inlet, outlet concentrations and inlet, outlet PSD's, the fractional efficiency curves of PM10 inlets were calculated by using equation 3. Cut-points and slopes were determined from the fractional efficiency curves. Table 3 shows the resulting PM_{10} inlet cut-points and slopes for each test. Cut-points larger than 10 μm indicate the over-sampling problem. The statistical analysis indicates that the average cut-points of P1/P2 are significantly different for cornstarch, fly ash and aluminum oxide. The cut-point increased with the 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.

The resulting cut-points and slopes calculated by using inlet PSD associated with low-volume TSP (T1) and high-volume TSP (HT1) are not significantly different. This suggests that both low-volume TSP and high-volume TSP samplers were capturing the PM with the same characteristics such as mass median diameter (MMD) and geometric standard deviation (GSD).

Conclusions

The following conclusions were made based upon results of this study:

1. 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.
2. The cut-points and slopes of PM_{10} pre-separator changed with the change of MMD's of inlet PM.
3. The fractional efficiency curve shifted to the right with the decrease of the MMD of the inlet PM. (This is a different conclusion that reported by Pargmann et al (2001). It is possible that particle density could play a role in the shift in cut point.)
4. PM_{10} sampler measurement errors increase with the decrease of the MMD of inlet PM. This is a different conclusion that reported by Buser et al (2002).
5. Analysis of the results suggest that co-locating PM_{10} and TSP samplers may offer a process that can be used to correct for PM_{10} sampler error.

References

Buser, M., C. B. Parnell, Jr., B. W. Shaw and R. E. Lacey. 2002. PM_{10} sampler errors due to interaction of particle size and sampler performance characteristics. Proceedings of the 2002 Beltwide Cotton Production Conferences. National Cotton Council. Memphis, TN.

Buser, M., C.B. Parnell, Jr., R.E. Lacy, and B.W. Shaw. 2001. Inherent biases of PM_{10} and $PM_{2.5}$ samplers based on the interaction of particle size and sampler performance characteristics. Paper No. 01-1167 presented at the 2001 ASAE Annual International Meeting in Sacramento, CA, St. Joseph, MI.

Boriack, C., L. B.Goodrich, C. B. Parnell, S. Mukhtar, B. W.Shaw, R. E. Lacey. 2003. Revised design of the total suspended particulate (TSP) sampler. Presented at the 2003 Beltwide Cotton Production Conferences. National Cotton Council. Memphis, TN.

McFarland, A. R. and C. A. Ortiz. 1983. Evaluation of prototype PM-10 inlets with cyclonic fractionators. APCA Paper No. 33.5, presented at the 76th Annual Meeting and Exposition, Air Pollution Control Association. Atlanta, GA.

Pargmann, A. R., C. B Parnell, Jr. and B. W. Shaw. 2001. Performance characteristics of PM 2.5 samplers in the presence of agricultural dusts. Paper No. 014008, presented at the 2001 ASAE Annual International Meeting in Sacramento, CA, St. Joseph, MI.

Pargmann, A. R 2001. Performance characteristics of PM 2.5 samplers in the presence of agricultural dusts. M.S. thesis, Department of Agricultural Engineering, Texas A&M University, College Station, TX.

U. S. Environmental Protection Agency. 2000b. 40CFR Part 53 National Ambient Air Quality Standards for Particulate Matter; Final Rule. Federal Register Vol. 65, No. 249. EPA, Washington, D.C.

Table 1. Resulting concentration (mg/m^3) from testing low-volume (1 m^3/hr) and high volume (85 m^3/hr) total suspended particulate matter (TSP) samplers with PM_{10} samplers. P1 and P2 are the PM_{10} samplers. T1 and T2 are the low-volume TSP samplers

		Low volume samplers				High volume
		P1	P2	T1	T2	TSP
Test #	Dust	Teflon filter	Teflon filter	Teflon filter	Teflon filter	Glass fiber filter
1	Corn starch	16	11	28	28	33
2	Corn starch	24	16	48	49	53
3	Corn starch	23	16	47	49	51
4	Corn starch	14	13	28	31	32
5	Corn starch	17	13	34	35	37
1	Fly ash	24	13	29	28	26
2	Fly ash	42	28	55	57	52
3	Fly ash	48	34	59	60	47
4	Fly ash	45	23	56	57	41
5	Fly ash	43	29	57	58	37
1	Aluminum oxide	29	18	30	33	23
2	Aluminum oxide	9	11	17	19	14
3	Aluminum oxide	29	18	27	29	20
4	Aluminum oxide	35	23	32	35	23
5	Aluminum oxide	26	17	24	28	14

Table 2. Comparisons of the measured PM_{10} concentration (mg/m^3) and PM_{10} ratio using two PM_{10} pre-separators and the calculated PM_{10}concentrations using measured TSP concentrations and PSD with TSP samplers

	TSP samplers	PM_{10} pre- separators

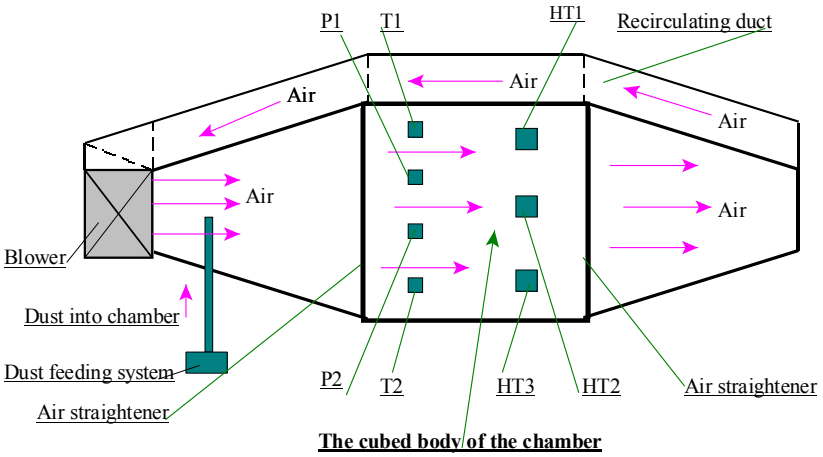
		T1			HTSP			P1		P2	
		TSP[1]	PM_{10}[2]	PM_{10}[3]	TSP[4]	PM_{10}[5]	PM_{10}[3]	PM_{10}[6]	PM_{10}[7]	PM_{10}[6]	PM_{10}[7]
Dust	Test #	Con.	(%)	Con.	Con.	(%)	Con.	Con.	(%)	Con.	(%)
	1	28	30	8	33	32	11	16	57	11	39
Corn	2	48	29	14	53	26	14	24	51	16	33
Starch	3	47	28	13	51	27	14	23	48	16	34
	4	28	22	6	32	19	6	14	49	13	44
	5	34	29	10	37	26	10	17	51	13	38
Average			**28%[a]**			**26%[a]**			**51%[b]**		**38%[b]**
	1	29	40	12	26	35	9	24	82	13	45
Fly	2	55	38	21	52	35	18	42	76	28	51
Ash	3	59	41	24	47	39	18	48	81	34	58
	4	56	46	26	41	44	18	45	80	23	41
	5	57	43	25	37	39	14	43	76	29	51
Average			**42%[b]**			**38%[b]**			**79%[c]**		**49%[b]**
	1	30	53	16	23	37	9	29	97	18	60
Alumi.	2	17	50	9	14	48	7	9	53	11	65
Oxide	3	27	52	14	20	50	10	29	108	18	67
	4	32	56	18	23	52	12	34	106	23	72
	5	24	52	12	14	54	8	26	108	17	71
Average			**52%[b]**			**48%[b]**			**94%[d]**		**67%[c]**

1. TSP concentration (mg/m^3) measured by low-volume TSP sampler (T1),
2. Percentage of PM_{10} from PSD of PM on the filter of T1 sampler,
3. PM_{10} concentration (mg/m^3) = TSP concentration (a) x PM_{10} ratio (b),
4. TSP concentration (mg/m^3) measured by high-volume TSP sampler (HT3) with glass fiber filter,
5. Percentage of PM_{10} from PSD of PM on the filter of high volume TSP sampler (HT1) with polyweb filter,
6. PM_{10} concentration (mg/m^3) measured by PM_{10} samplers,
7. (PM_{10}/TSP) ratio = (PM_{10} concentration measured by PM_{10} sampler) / (TSP concentration measured by T1),
8. Means with the same letter are not significantly different at 0.05 levels.

Table 3. PM_{10} inlet cu-points and slopes[1]

		reference inlet PSD and con. from T1[2]				reference inlet PSD and con. from HT1 & 3[3]			
		P1		P2		P1		P2	
Dust	Test #	d_{50}	slope	d_{50}	slope	d_{50}	slope	d_{50}	slope
	1	13.0	1.30	11.5	1.42	13.5	1.20	12.0	1.42
Corn	2	12.5	1.40	11.0	1.45	12.5	1.45	11.5	1.45
Starch	3	12.5	1.25	11.0	1.45	13.0	1.25	12.0	1.45
	4	13.5	1.20	14.0	1.30	13.5	1.20	14.0	1.30
	5	12.6	1.26	11.5	1.40	12.8	1.30	12.0	1.40
Average		**12.8[a]**	**1.28**	**11.8[a]**	**1.40**	**13.1[a]**	**1.28**	**12.3[a]**	**1.40**
	1	17.0	1.30	13.5	1.60	18.0	1.40	12.0	1.90
Fly	2	17.0	1.30	15.5	1.62	17.0	1.30	14.5	1.80
Ash	3	17.5	1.25	17.5	1.40	16.5	1.30	15.0	1.80
	4	19.0	1.30	15.0	2.10	17.0	1.42	12.0	2.50
	5	18.5	1.25	17.5	1.40	16.0	1.40	13.0	1.90
Average		**17.8[b]**	**1.28**	**15.8[b]**	**1.62**	**16.9[b]**	**1.36**	**13.3[a]**	**1.98**
	1	22.5	1.25	19.0	1.40	22.0	1.30	18.0	1.50
	2	11.0	1.40	19.0	1.60	11.0	1.70	16.5	1.65
Alum.	3	22.0	1.35	21.0	1.45	18.0	1.40	15.0	1.70
Oxide	4	24.0	1.20	20.5	1.35	23.0	1.20	20.0	1.30
	5	24.0	1.30	24.0	1.30	19.0	1.30	17.0	1.70
Average		**20.7[c]**	**1.30**	**20.7[c]**	**1.42**	**18.6[c]**	**1.38**	**17.3[c]**	**1.57**

1. Cut-points & slopes were obtained from fractional efficiency curves, which were calculated using inlet and outlet concentrations and particle size distributions (PSD's) (equation 3),
2. PM concentrations measured by T1 sampler and PSD of PM on the T1 filters were used as inlet PM concentration and inlet PSD of PM for the fractional efficiency calculations.
3. PM concentrations measured by HT3 sampler and PSD of PM on the HT1 filters were used as inlet PM concentration and inlet PSD of PM for the fractional efficiency calculations.
4. Means with the same letter are not significantly different at 0.05 levels.



P1-PM_{10} pre-separator #1, P2-PM_{10} pre-separator #2, T1-low-volume TSP sampler #1, T2- low-volume TSP sampler #2, HT1-high volume TSP sampler #1, HT2 - (modified) high volume TSP sampler #2, HT3-high volume TSP sampler #3

Figure 1. Top view of the dust chamber and sampler set-up

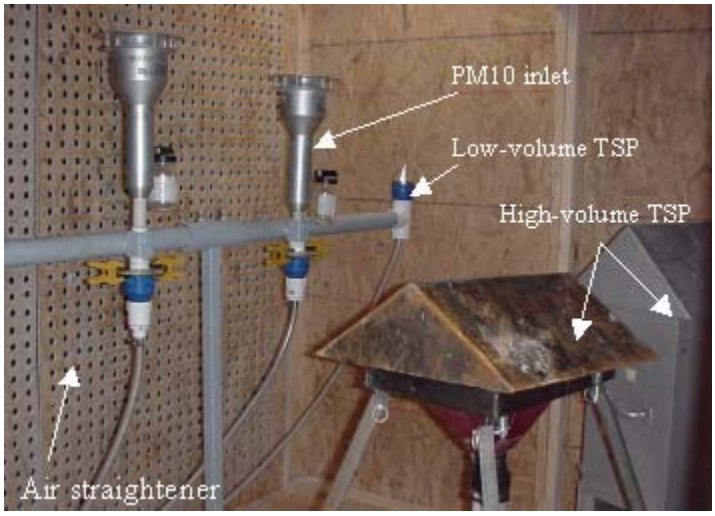


Figure 2. Sampler set-up inside the chamber and air straightener

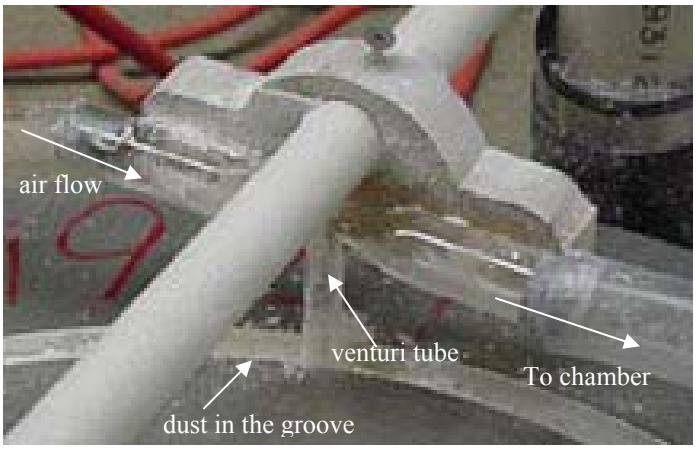


Figure 3. Dust feeding system – venturi tube
(adapted from A.R. Pargamnn's M. S. thesis, 2001)

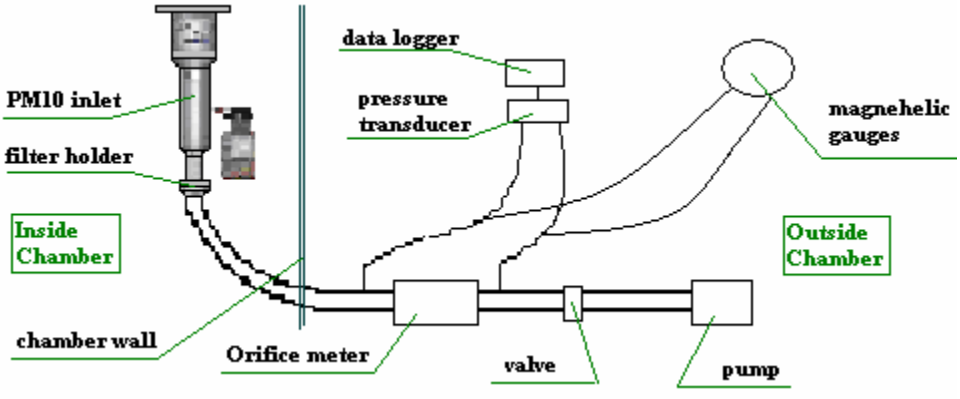


Figure 4. PM_{10} pre-separator sampling (testing) system