

THE DESIGN AND EVALUATION OF A LOW-VOLUME TOTAL SUSPENDED PARTICULATE SAMPLER

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Abstract

The regulation of particulate matter (PM) emitted by agricultural sources (cotton gins, feed mills, concentrated animal feeding operations (CAFOs)) is based upon downwind concentrations of particulate matter less than 10 and 2.5 micrometers (μm) (PM_{10} and $\text{PM}_{2.5}$) aerodynamic equivalent diameter (AED). Both PM_{10} and $\text{PM}_{2.5}$ samplers operate by pre-separating PM larger than the size of interest (10 and 2.5 μm) prior to capturing the PM on the filter. It has been shown that Federal Reference Method (FRM) PM_{10} and $\text{PM}_{2.5}$ samplers have concentration measurement errors (Buser et al, 2001, 2002) when sampling PM in ambient air having mass median diameters (MMD) larger than the size of interest. It has also been demonstrated that most PM from agricultural sources typically have particle size distributions with MMDs larger than 10 μm (AED). The PM_{10} concentration measurement error can be as much as 343% for ambient PM with an MMD=20 μm . These errors are a consequence of the PM_{10} pre-separator allowing a larger mass of PM greater than 10 μm to penetrate to the filter than the mass of PM less than 10 μm captured by the pre-separator. The mass of the particles greater than 10 μm that are allowed to penetrate to the filter, introduce a substantial error in the calculated concentration of PM_{10} . Pargmann et al (2001) reported that sampling PM larger than 2.5 μm (AED) resulted in a shift in the cut-point of the pre-separator. If this is true for all PM_{10} and $\text{PM}_{2.5}$ samplers, the resulting errors in measurements of ambient concentrations could be even larger than those reported by Buser.

One solution to this problem is to measure the concentration of total suspended particulate matter (TSP) and calculate the concentration of PM_{10} by determining the mass fraction of PM less than size of interest from the particle size distribution (PSD). The "standard" high volume (TSP) sampler operates at a volume rate-of-flow in excess of 40 cubic feet per minute (cfm) (EPA, 1987b). Most of the current PM_{10} and $\text{PM}_{2.5}$ samplers operate at one cubic meter per hour (cmh). (1 cmh = 0.589 cfm.) McFarland (1983) reported that TSP samplers have a "cut-point" of a nominal 45 μm (AED). EPA specifies the engineering design parameters for TSP samplers in 40CFR Part 50 (1987b). This paper reports the engineering design and evaluation of a low-volume (0.589 cfm) TSP sampler (TSP_{LV}). The results suggest that this new TSP_{LV} may be more robust and more accurate than the "standard" high volume (TSP) sampler.

Introduction

Before 1987, the United States Environmental Protection Agency (EPA) regulated particulate matter (PM) emission sources based upon a measure of the total suspended particulate (TSP). In 1987, the EPA began regulating PM pollution sources based on the 24-hour property line concentration of PM_{10} (52 Federal Register 29383, Aug. 7, 1987). PM_{10} as defined by EPA 40CFR Part 50 (1999) is the concentration of PM with an aerodynamic diameter (AED) of less than or equal to a nominal 10 μm . The National Ambient Air Quality Standard (NAAQS) mandates that public exposure to the 24-hour ambient concentration of PM_{10} should be no more than 150 $\mu\text{g}/\text{m}^3$ (40CFR Part 50, 1999). Some states have viewed the NAAQS as a property line concentration limit not-to-be exceeded.

The EPA Federal Reference Method PM_{10} sampler defined in 40CFR Part 53, is designed to have a nominal cut point of $10 \pm 0.5\mu\text{m}$ with a slope of $1.5 \pm .1$ (Buser, 2001). Agricultural dusts typically have particle size distributions (PSD) characterized by an MMD between 10 and 20 μm with a GSD ranging from 1.5 to 2.0. It has been shown that a FRM sampler sampling in ambient conditions with MMD equal to 20 μm could over sample by as much as 181 to 343% (Buser, 2001).

It is becoming more common practice to measure concentrations of PM_{10} and $\text{PM}_{2.5}$ on a low volume basis. Low-volume sampling is sampling ambient air at a flow rate of 1 cubic meter per hour. The Tapered Element Oscillation Method (TEOM) sampler is a low-volume sampler. When the TEOM is equipped with the proper pre-separator it is used to measure concentrations of PM_{10} or $\text{PM}_{2.5}$. However, all PM_{10} or $\text{PM}_{2.5}$ concentration measurements equipped with FRM pre-separators will be in error when sampling PM with an MMD larger than 10 and 2.5 μm , respectively.

TSP measurements are currently being taken using low volume samplers by means inconsistent with the guidelines set forth for a TSP sampler by 40 CFR Part 50, App. B. As defined, the TSP pre-separator has a gabled hood that should overhang the filter housing "somewhat" so as to form an inlet gap that is approximately equal on all sides. This inlet gap is to be designed so as to provide a particle capture air velocity between 20 and 35 cm/sec. This capture air velocity provides the nominal cut-point for the TSP sampler. According to McFarland et al (1983), the TSP pre-separator has a cut-point of approximately 45 μm with a slope of 1.5.

Design

Currently, there are no guidelines set for the design of a low-volume TSP sampler. The low-volume TSP pre-separator (TSP_{LV}) designed by the Center for Agricultural Air Quality Engineering and Science (CAAQES) at Texas A&M University was designed based upon the applicable guidelines for a high volume TSP sampler in 40 CFR Part 50, Appendix B (1987).

The critical design points that were maintained from the high volume method were the capture air inlet area and the gabled roof design (modified to accommodate a circular shaped base). The capture air inlet area is critical to the performance of the sampler because the capture air velocity is a direct function of this area. The capture air inlet area shown in figure 1 is the area between the inside bottom diameter of the cone and the outer diameter of the hood base. Equation 1 was used to calculate the minimum and maximum capture air inlet area for the range of capture air velocities given in 40 CFR Part 50 (1987).

$$CAIA = \frac{ASF}{CAV} * 1.667 \quad (\text{Equation 1})$$

where

- CAIA = capture air inlet area, m²;
- ASF = air sampling flow rate, m³/min;
- CAV = capture air velocity, cm/s; and
- 1.667 = conversion factor.

Once the maximum and minimum values for the CAIA were established using the maximum and minimum CAV values of 35 and 20 cm/s respectively, a convenient dimension was chosen within the limits for the CAIA. The TSP_{LV} hood base (shown in figure 1) was designed to attach directly to the 47mm filter holder manufactured by *F and J Specialty Products, inc.* The height of the base was chosen so that disassembly of the pre-separator from the filter holder would be trouble free. With the diameter of the outer edge of the hood base known, equation 2 was used to calculate the inner base diameter of the TSP_{LV} hood/cone.

$$D_2 = \sqrt{D_1^2 + \frac{CAIA_a * 4 * 10^6}{\pi}} \quad (\text{Equation 2})$$

where

- D₂ = Inner hood/cone diameter, mm;
- D₁ = Hood base outer edge diameter, mm;
- CAIA_a = Chosen CAIA dimension within range calculated above, m²;
- 10⁶ = Conversion Factor.

With the inner hood/cone diameter established, the wall thickness of the hood/cone was chosen and added to the inner radius of the hood/cone to determine the outer radius. The angle of the cone vertex is not overly critical, but was chosen arbitrarily at 80 degrees. The bottom edge of the hood/cone overhangs the top surface of the hood base somewhat as per the guidelines for the high volume TSP sampler.

Each TSP_{LV} pre-separator was machined using 6061 aluminum stock. The posts used to fix the height of the hood above the hood base were mild steel but aluminum could have been used. The separate components of the pre-separator were assembled and joined together using a high strength epoxy adhesive.

Testing Protocol

The TSP_{LV} samplers fitted with pre-separators were tested in a controlled particulate concentration air chamber in the CAAQES Processing Lab at Texas A&M University. This is the same chamber described by Pargmann et al (2001). The test protocol consisted of co-locating two TSP_{LV} samplers with two low-volume PM₁₀ samplers and three high-volume TSP samplers. The two PM₁₀ samplers utilized Graseby-Andersen PM₁₀ inlets. Figure 3 shows the arrangement of the samplers in the chamber. The following are additional details of the sampling protocol:

- Each test was one hour in duration.
- Initially, the high-volume circulating fan in the chamber was turned on to begin circulating the air in the chamber.
- Next the dust was fed into the chamber once the air circulation rate was established.

- Three different dusts were used in the experiments.
 - corn starch (MMD 18.6 μm , GSD 1.4)
 - fly ash (MMD 13.0, GSD 2.4)
 - aluminum oxide (MMD 9.03, GSD 1.4).
- Five tests were conducted with the 2 high-volume TSP, two low-volume TSP and 2 low-volume PM₁₀ samplers co-located in the chamber used to measure concentration and 1 high-volume TSP used to capture dust for particle sizing with each of the 3 test dusts. In effect, the test was concentration measurements with two low- and high-volume TSP samplers and two PM₁₀ samplers with 3 dust and 5 replications.
- The chamber was cleaned after all of the replications of one dust were made before the new dust was used.
- At the end of each test, the filters were collected from the samplers and placed back into their protective containers. (Technicians used latex gloves and small tongs to prevent any contamination of the filter media.)
- The filter number, beginning and end time and magnehelic gage pressure was recorded in a log sheet for each test.
- The low-volume pre-separators were operated at 1 m³/hr volumetric airflow rate.
- 47mm diameter Teflon filters were used as the filter media for the tests.
- Each of the low volume pre-separators used a diaphragm pump (Dayton, 4Z792) to provide the required airflow rate.
- A sharp edge orifice plate was used to monitor the airflow rates through the samplers.
- The pressure drop across the orifice was monitored using a pressure transducer (Omega, PX274, Omega Engineering Inc., Stamford, CT) and also with a magnehelic gage for a visual check.
- The airflow rate was controlled using a needle valve. A data logger (HOBO H8 RH/Temp/2x External, Onset Computer Corp, Pocasset, MA) recorded the output of the pressure transducer at 12-second intervals.
- The three high-volume TSP samplers were operated at the required air-flow rate of 1.42 m³/min (50 cfm) using a centrifugal fan.
- One high-volume TSP sampler used poly-web filter media for the subsequent particle size distribution analyses. The other two used glass fiber filters to obtain samples for concentration measurements.
- The air-flow rates across the filters for the high-volume samplers were calculated using the pressure drop across a sharp edge orifice plate. (The pressure drop was obtained using the same pressure transducer and magnehelic gage used in the low-volume systems.)
- The same data loggers were used to record 12-second pressure transducer readings.
- The filters were all conditioned in an environmental chamber for 24 hours before being pre-weighed prior to the tests.
- The loaded filters (following testing) were also conditioned in the same environmental chamber before being weighed.
- All filters were weighed using a high-precision analytical balance (AG245, Mettler Toledo, Greifensee Switzerland) in the environmental chamber.

Concentration and PSD Calculations

One-hour concentrations were calculated using the 12-second flow rates and the weight differentials from each of the filters. The 12-second pressure drop readings were used to calculate a volume flow for the 12-second intervals. The sum of these flow volumes was used in the concentration calculation. Equation 3 was used to calculate the one-hour concentrations.

$$C_{1Hr} = \frac{\Delta M}{V_{air}} \quad (\text{Equation 3})$$

where

- C_{1Hr} = one hour concentration, mg/m³;
- ΔM = Mass differential of unloaded and loaded filters, mg; and
- V_{air} = Integrated sum of 12 second flow rates, m³.

Particle size distributions were obtained from the Teflon and poly web filters using the Coulter Multisizer3 (Beckman – Coulter).

Results and Discussion

The concentration data, shown in Table 1, shows very consistent concentration measurements between the two TSP_{LV} pre-separators. The results of testing the null hypothesis that there is no significant difference in the measured concentrations of the two TSP_{LV} pre-separators with a t-test ($\alpha=0.05$ level) were a rejection of the null hypothesis. There was no difference in the measured concentrations by the two TSP_{LV} pre-separators. The t-test ($\alpha=0.05$ level) was used to test the null hypothesis that there was no difference in the concentration measurements made by high- and low-volume TSP samplers for the corn starch tests. The results indicate that there was no significant difference between the measured concentrations by the low-volume TSP samplers and the high-volume TSP samplers. Over all of the tests, the average difference in measured concentration of the two low volume samplers was 1.8 mg/m³.

A particle size distribution was determined from each filter from the TSP_{LV} pre-separators and the high-volume TSP sampler (HT1). The average PSDs for each low volume TSP sampler and high volume sampler over all of the corn starch, fly ash, and aluminum oxide tests are shown in Figures 3, 4, and 5 respectively. This figure illustrates the similar performance characteristics between the TSP_{LV} pre-separators and the high volume TSP sampler. An analysis of variance test (ANOVA) using Tukey's Studentized Range (HSD) ($\alpha = .05$) shows that there is no significant difference in the performance of the low volume TSP pre-separators and the high volume TSP sampler over any of the dusts at an applicable level. There was a significant difference detected between the two TSP_{LV} pre-separators and the high volume TSP sampler with the fly ash test results. However, the magnitude of the difference is relatively small. TSP_{LV} pre-separators measured the MMD at 1 μm less than that measured by the high volume TSP sampler. Table 2 shows the average MMD and GSD data for the two TSP_{LV} pre-separators and also for the high volume TSP sampler.

The data from the data loggers show that the flow rate of the TSP_{LV} pre-separators was held relatively constant over the entire time of each test, while the flow rates of the high-volume TSP samplers were reduced as filter loading increased. As a consequence, the speeds of the centrifugal fans operating the high-volume samplers were increased during the tests to maintain the required flow rate. It is assumed that the larger variation in airflow rates of the high-volume TSP samplers contributed to the higher variability of the TSP concentration measurements relative to the TSP_{LV} sampler results. Two factors may have contributed to these results:

- The loading rate of the low-volume sampler filters was significantly lower due to the decreased airflow rate per unit area. (Assuming a constant PM concentration in the ambient air being sampled, the loading on a 20.3 x 25.4 cm high-volume TSP sampler filter is 286% higher than the loading on a low volume TSP 47mm diameter filter.)
- The lower penetration velocity of the low-volume TSP samplers (9.6 m³/m²/min) relative to the high-volume TSP samplers (27.4 m³/m²/min) resulted in a lower pressure drop across the filter allowing the sampler to operate in high concentrations for longer periods of time. This lower penetration velocity may have increased the capture efficiency of the filter.

Conclusions

The results of this study suggest the following:

- An accurate measurement of TSP is possible with a low-volume (1 m³/h) sampler (TSP_{LV}) provided a properly designed TSP pre-separator is used.
- The accuracy and consistency of both low- and high-volume TSP concentration measurements provide a solid basis from which more accurate PM₁₀ concentrations determinations can be made for PM having MMDs larger than 10 μm (AED).
- Use of TSP concentrations and mass versus particle size PSDs will prevent the measurement errors associated with PM₁₀ pre-separators in ambient dusts with MMDs greater than 10 μm .
- The concentration and PSD data from these series of tests suggest that the TSP_{LV} sampler had less variability than the high-volume TSP samplers. (These tests will be repeated in the spring of 2003 prior to publication.)
- A TSP_{LV} sampling system also provides reduced cost of initial investment and operation. Smaller filters, pump units, and reduced energy requirements all contribute to the low cost of the systems.
- The lower penetration velocity relative to the high-volume TSP sampler avoids the significant increase in pressure drop across the filter during the sampling period due to increased loading rates. This factor allows for less variability of flow rate as well.
- The low-volume systems are light weight and can easily be used in field applications.

Field tests of low-volume TSP samplers with associated pre-separators are planned for the spring 2003.

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Table 1. Concentration measurement results for 15 tests in a controlled concentration chamber with three test dusts (corn starch, fly ash, and aluminum oxide). Two low-volume (1 m³/hr) TSP samplers (T1 and T2) fitted with a designed TSP pre-separator and one high-volume (85 m³/hr) sampler (TSP3).

Test #	Dust	Concentration (mg/m ³)		
		1 m ³ /hr		85 m ³ /hr
		T1	T2	TSP3
		Teflon	Teflon	Glass Fiber
6	Corn Starch	28.00	28.00	33.14
8	Corn Starch	48.00	49.00	53.30
9	Corn Starch	47.00	49.00	50.98
10	Corn Starch	28.44	31.40	32.42
11	Corn Starch	33.90	35.10	37.00
12	Fly Ash	29.00	28.00	26.23
13	Fly Ash	55.00	57.00	51.60
14	Fly Ash	59.00	60.00	47.30
15	Fly Ash	56.00	57.20	41.00
16	Fly Ash	57.00	58.00	36.60
17	Alum. Oxide	30.00	33.00	22.80
18	Alum. Oxide	17.00	19.00	13.80
19	Alum. Oxide	27.00	29.00	20.00
20	Alum. Oxide	32.00	35.00	22.70
21	Alum. Oxide	24.00	28.00	14.30

Table 2. Average particle size distribution results for the low- and high-volume sampler tests. The data reported include average mass median aerodynamic equivalent diameters (MMD) in micrometers (μm) and geometric standard deviations (GSD) of the two low- and 1 high-volume samplers tested (T1, T2, and HT1, respectively). MMDs with the same superscript letter are not significantly different using Tukey's Studentized Range ($\alpha = .05$).

Sampler	Corn Starch Avg.		Fly Ash Avg.		Alum. Oxide Avg.	
	MMD	GSD	MMD	GSD	MMD	GSD
T1	14.1 ^a	1.7	12.0 ^a	2.1	9.6 ^a	2.0
T2	13.9 ^a	1.6	11.8 ^a	2.0	9.6 ^a	1.9
HT1	14.5 ^a	1.7	13.0 ^a	2.0	10.3 ^a	2.0

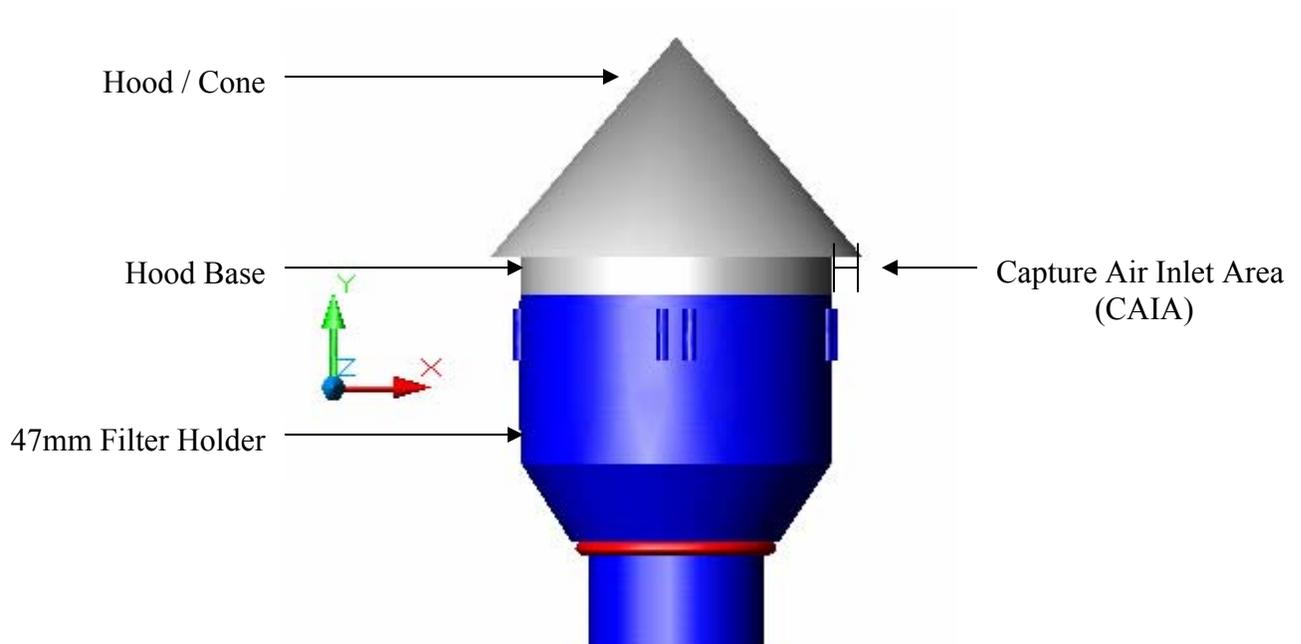


Figure 1. Illustration of the side view of the low-volume pre-separator used with the low-volume TSP sampler.

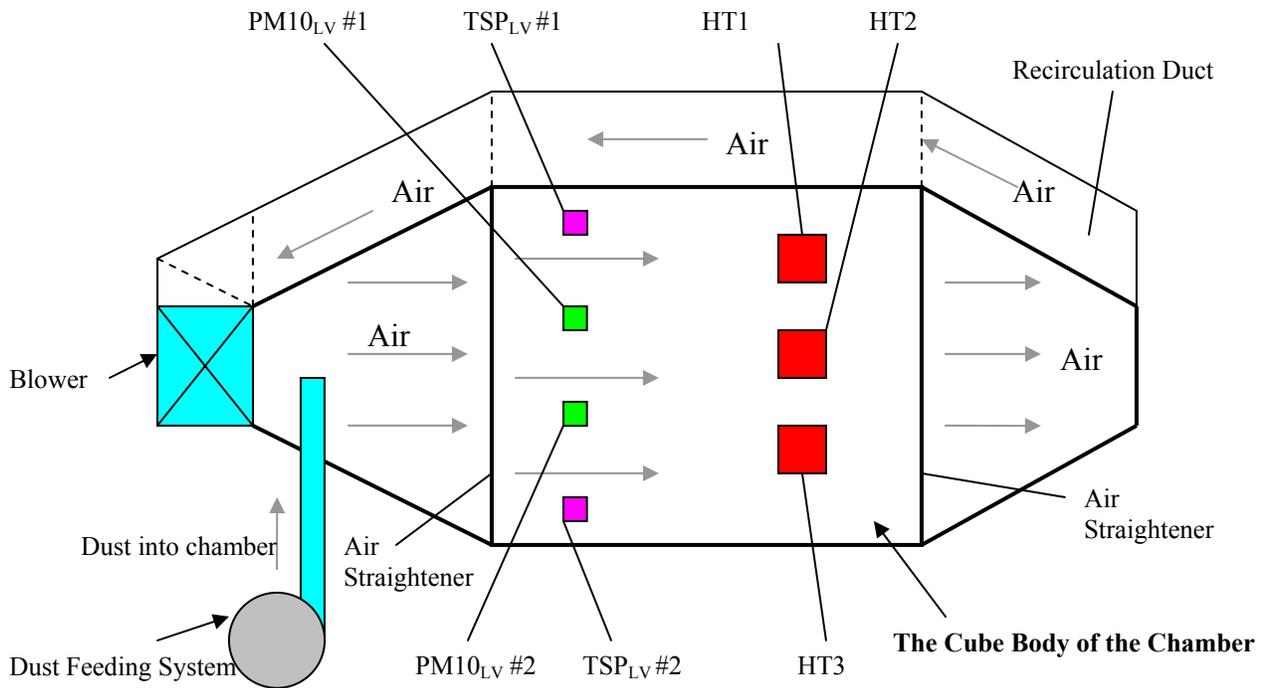


Figure 2. Schematic diagram of the “constant concentration” test chamber and the relative locations of the samplers in the chamber. This chamber was used to evaluate co-located low- and high-volume TSP and PM₁₀ samplers. (See Pargmann et al, 2001.) Note that the two low-volume TSP (TSP_{LV#1} and TSP_{LV#2}) samplers were near the wall. The high volume samplers are HT1, HT2, and HT3.

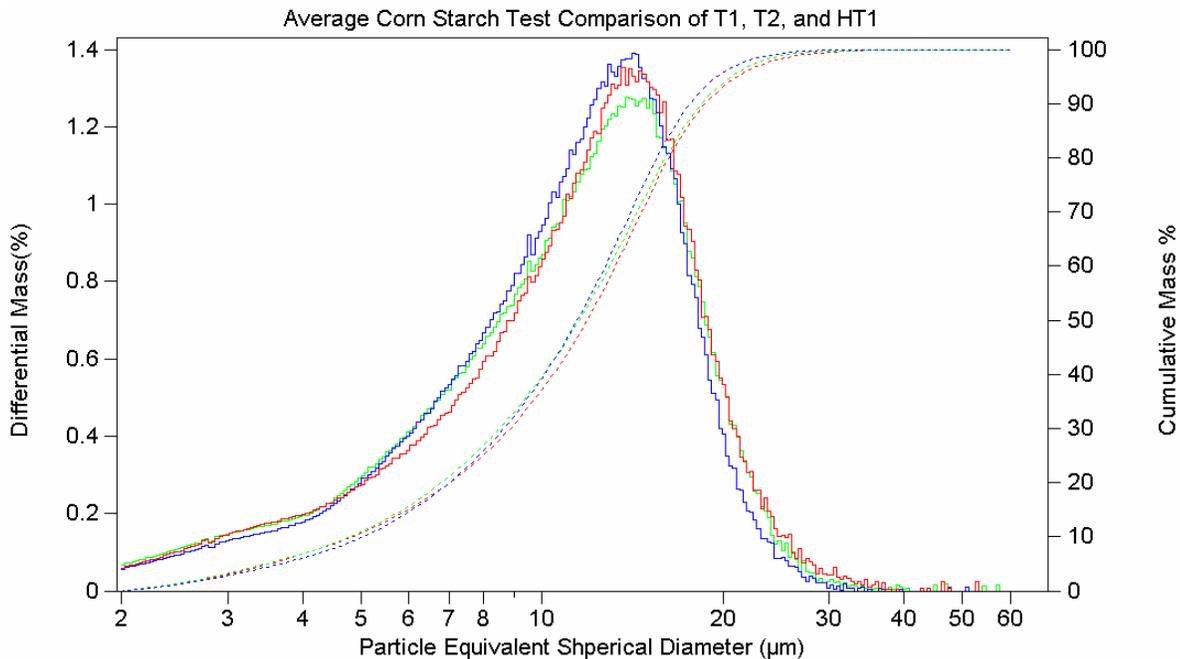


Figure 3. Results of PSD analyses for PM captured with low-volume TSP samplers – T1 and T2 and high volume sampler – HT1 for the corn starch tests. Both the differential and cumulative PSDs are shown.

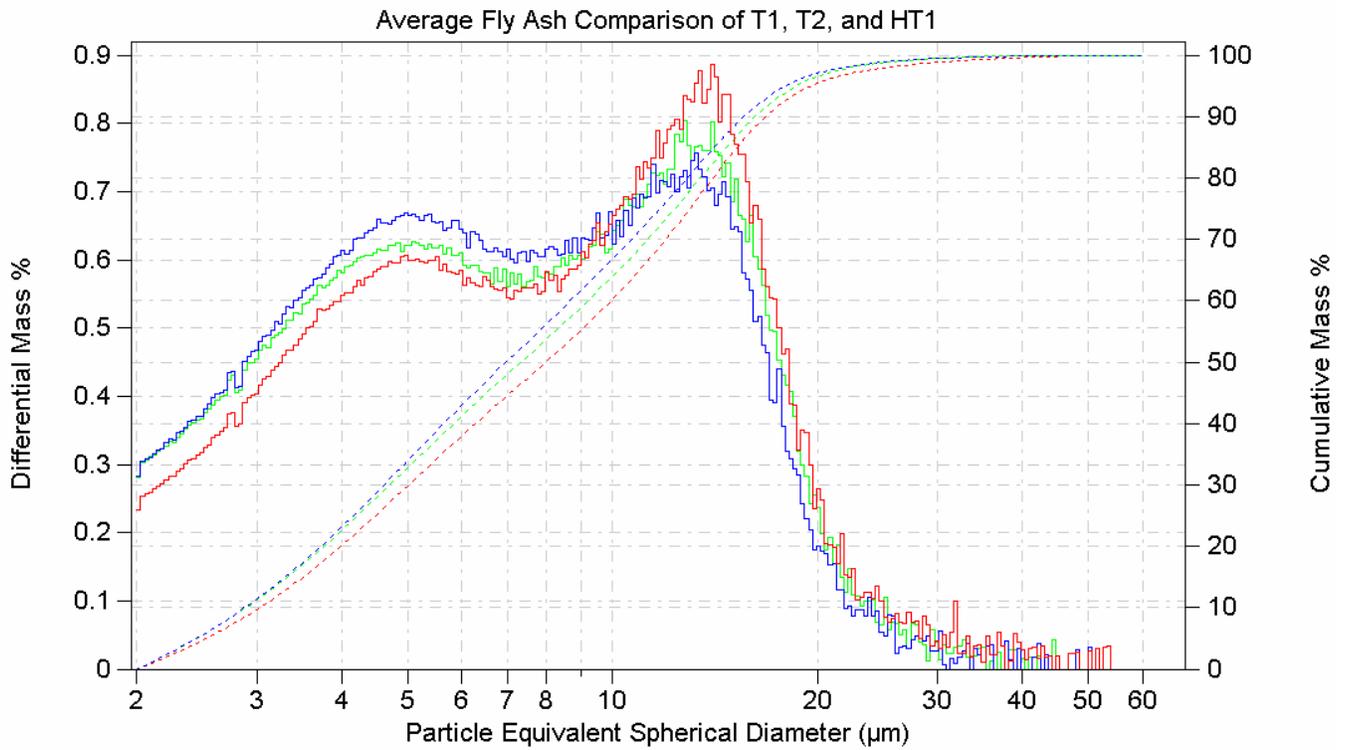


Figure 4. Results of PSD analyses for PM captured with low-volume TSP samplers – T1 and T2 and high volume sampler – HT1 for the fly ash tests. Both the differential and cumulative PSDs are shown.

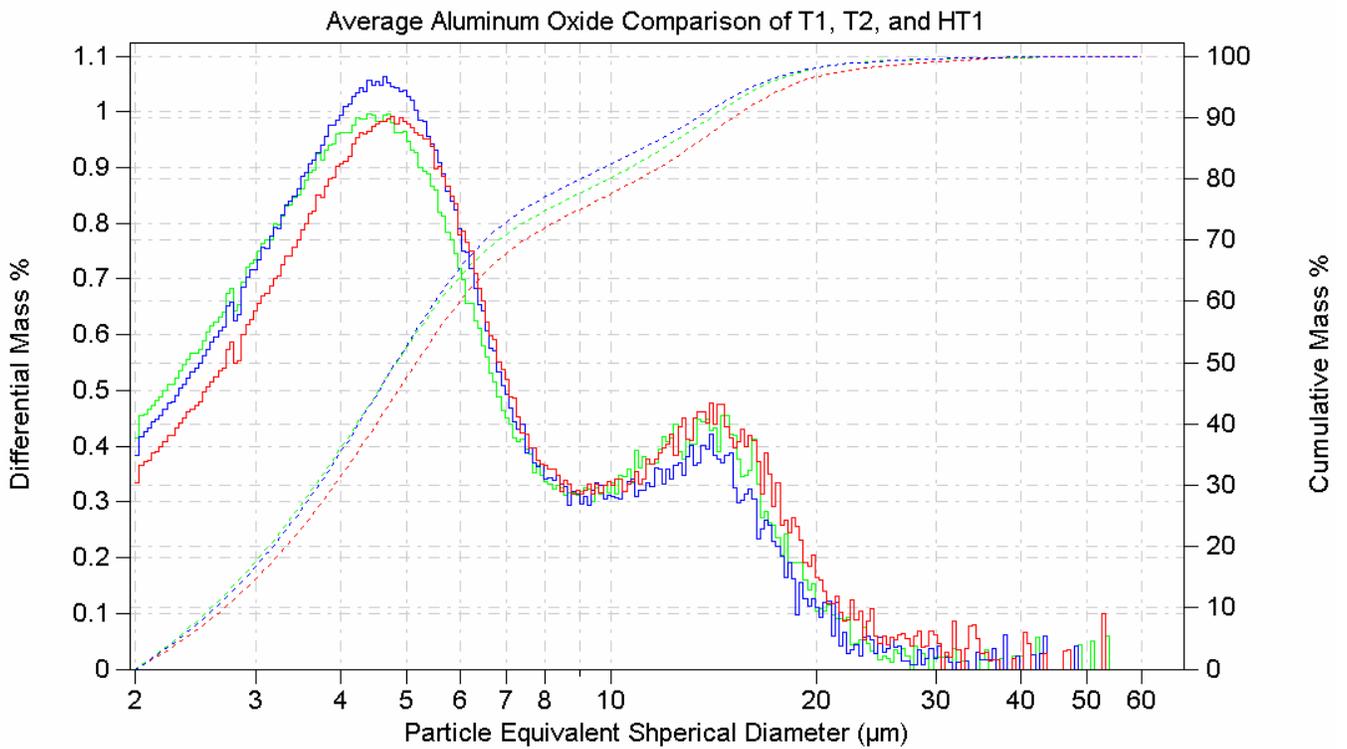


Figure 5. Results of PSD analyses for PM captured with low-volume TSP samplers – T1 and T2 and high volume sampler – HT1 for the aluminum oxide tests. Both the differential and cumulative PSDs are shown.