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PARTICLE SIZE DISTRIBUTION ANALYSIS OF COTTON GIN DUST AND ITS IMPACT ON PM10 CONCENTRATION MEASUREMENTS

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Abstract

Low volume FRM PM_{10} and TSP (total suspended particulate) samplers were collocated and operated directly downwind from a cotton gin's main sources of emissions while the facility was in full operation. The particle size distribution and concentration of dust collected by the TSP sampler were used to determine the true PM_{10} concentrations and compare them with the PM_{10} concentrations measured by the low volume PM_{10} sampler. Results showed that in all instances, the concentrations measured by the PM_{10} sampler were in error and higher than the PM_{10} concentrations obtained from using the TSP sampler. A linear relationship existed between the true PM_{10} concentration and the concentration from the PM_{10} sampler. Specifically, the results of this study have indicated the following: (a) 55% of the PM_{10} concentration reported by the FRM PM_{10} sampler was considered true PM_{10} throughout the range of PM concentration measured; (b) 35% of the TSP sampler concentration comprised PM_{10}; (c) the lognormal distribution accurately described the PSD of the cotton gin dust; and (d) the use of the TSP sampler followed by measurement of mass median diameter (MMD) and geometric standard deviation (GSD) was found to be a better approach in reporting PM_{10} concentrations of agricultural dusts such as that from cotton gins.

Introduction

Not all countries categorize PM_{10} samplers in the same manner. For instance, in the United States a PM_{10} sampler is classified as having a penetration curve with a cutpoint of 10 µm while other countries (e.g. Japan) classify a PM_{10} sampler as rejecting (removing from the air stream) all particles greater than 10 µm *(USEPA, 2003)*. A significant step in the standardization process of aerosol sampling was the EPA definition *(USEPA, 1987)* of the PM_{10} size fraction, based on the aerodynamic equivalent diameter (AED) of particles capable of penetrating to the thoracic region of the respiratory system. This definition was followed by the implementation of EPA's PM_{10} Ambient Air Monitoring Reference and Equivalent Methods regulation. The Equivalent Methods regulation format included the adoption of performance specifications for aerosol samplers based on controlled wind tunnel testing with mono-dispersed aerosols *(USEPA, 1996)*.

PM_{10} samplers are designated by EPA as reference or equivalent methods under the provisions of 40 CFR, Part 53 *(CFR, 2001a)*. PM_{10} reference methods must use the measurement principle and meet additional specifications set forth in 40 CFR, Part 50, Appendix J *(CFR, 2001b)*. Reference method PM_{10} samplers must also meet the requirements specified in 40 CFR, Part 53, Subpart D. Appendix J specifies a measurement principle based on extracting an air sample from the atmosphere with a sampler that incorporates inertial separation of the PM_{10} size range particles followed by collection of the PM_{10} particles on a filter over a 24-hour period. Alternatively, equivalent PM_{10} methods are not required to conform to the measurement principle specified in Appendix J or meet the additional Appendix J requirements *(USEPA, 1996)*. Instead, equivalent PM_{10} methods must meet the performance specifications set forth in 40 CFR, Part 53, Subpart D and demonstrate comparability to a reference method as required by 40 CFR, Part 53, Subpart C.

A number of samplers have been designated as PM_{10} reference or equivalent method samplers *(USEPA, 2001b)*. Mass concentration measurements with reproducibility close to 10% have been obtained with collocated samplers of identical design *(USEPA, 1996)*. However, field studies of collocated EPA approved PM_{10} samplers have shown substantial errors under certain conditions. These errors result from 1) allowing a tolerance of +/- 0.5 μm for the 10 μm cutpoint; 2) cutpoint deviations, beyond the established tolerances, associated with various field application parameters; 3) inadequate restrictions on internal particle bounce; 4) surface overloading; 5) soiling of certain types of PM_{10} inlets; and 6) losses of semi-volatile components. According to the USEPA *(USEPA, 1996)*, the most significant performance flaws have combined to produce excessive (up to 60%) mass concentration errors.

Wang et al. (2003) evaluated Graseby-Andersen FRM PM_{10} samplers in a dust chamber where the samplers were exposed to treatments of dispersed cornstarch, fly ash, and aluminum oxide. They reported that the Graseby-Andersen FRM PM_{10} sampler over-sampled the dispersed cornstarch, fly ash, and aluminum oxide by an average of 89%, 41%, and 14%, respectively. They also reported that the average cutpoint and slope for the Graseby-Andersen sampler was 12.5 μm and 1.3 when sampling cornstarch; 17.7 μm and 1.5 when sampling fly ash; and 17 μm and 1.5 when sampling aluminum oxide. Wang et al. (2003) concluded that the Graseby-Andersen FRM PM_{10} sampler's fractional efficiency curve shifted to the right when sampling dust with higher MMDs.

Buser (2004) conducted extensive mathematical simulations to illustrate the theoretical errors associated with EPA approved ambient PM_{10} samplers. In the study, Buser (2004) summarized the results with a scenario that assumed EPA approved PM_{10} ambient air samplers are set up to monitor two commercial operations. These samplers were assumed to have performance characteristics described by a d_{50} of 10.5 μm and a slope of 1.6 (both parameters are within the performance criteria defined by EPA). It was assumed that one operation was a power plant and was emitting PM (sampled by the PM_{10} sampler) that can be described by a lognormal distribution with a MMD of 5 μm and a GSD of 1.5. The second operation was assumed to be an agricultural operation emitting PM (sampled by the PM_{10} sampler) described by a lognormal distribution with a MMD of 20 μm and a GSD of 1.5. Further, the PM_{10} sampler used to monitor each of the operations was assumed to measure 100 $\mu g/m^3$. Results from this scenario indicated that 96% of the PM emitted from the power plant corresponded to particles with a diameter of 10 μm or smaller (true PM_{10}) and that the PM_{10} sampler under-estimated the true PM_{10} concentration by 8%. For the agricultural operation, results indicated that 4.37% of the emitted PM corresponded to PM with a diameter of 10 μm or smaller and that the PM_{10} sampler over-estimated the true PM_{10} by 245%. Based on this scenario, Buser (2004) concluded that the two operations are not being equally regulated (i.e. 109% of the PM emitted from the power plant and measured by the PM_{10} sampler corresponds to PM less than 10 μm; whereas only 29% of the PM from the agricultural operation and measured by the PM_{10} sampler corresponds to PM less than 10 μm).

The ultimate goal of a PM sampler is to accurately measure the concentration of specific ranges of particle sizes that exist in the atmosphere. However, it is not currently possible to accurately characterize the material that exists as particles in the atmosphere because of difficulties in creating a reference standard for particles suspended in the atmosphere. No calibration standards for suspended particle mass exist. As a result, the EPA defines accuracy for PM measurements in terms of the agreement between a candidate sampler and a reference sampler under standardized conditions for sample collection, storage, and analysis *(USEPA, 1996; USEPA, 2001a)*. Sampler comparisons thus become very important in determining the reproducibility of sampler measurements (measurement precision, as defined by EPA) and how sampler design influences accuracy *(USEPA, 2001a)*. The purpose of this research is to provide experimental data that can be coupled with previous theoretical research to characterize the errors associated with an EPA-approved ambient PM_{10} sampler that is deployed downwind from a cotton gin.

Study Objectives

The overall goal of this study was to find ways to assess and correct for over sampling bias of FRM PM_{10} samplers when used in agricultural facilities. The specific objectives are as follows:

a. To develop a relationship between a collocated PM_{10} and TSP sampler concentration measurements;
b. To determine the true PM_{10} from the particle size distribution (PSD) analysis of TSP filters;
c. To estimate the magnitude of over sampling bias and find ways on how to correct for over sampling bias.

Methodology

Samplers

Low volume TSP and PM_{10} samplers both developed at the Center for Agricultural Air Quality Engineering and Sciences (CAAQES) of the Biological and Agricultural Engineering Department (BAEN), Texas A&M University (TAMU) were used in this study. These samplers used 47 mm diameter Zefluor membrane filters to capture the ambient dust. The volumetric flow rate of 1 m^3/hr was used and the units were designed following EPA criteria. These low volume samplers provide better flow control compared with high volume samplers and were expected to give better quality results. The two types of sampler units were identical in design except for the inlet head used as pre-separator. The PM_{10} inlet head used was the Graseby-Andersen FRM PM_{10} sampler pre-collector (Wang et al. 2003) while the TSP inlet head used was that designed at TAMU (Wanjura et al. 2003).

Location and Description of the Cotton Gin and Placement of Samplers

The cotton gin used for this study was located in South Texas. This gin was operating at a rate of between 54-56 bales per hour during the tests. Shown in Figure 1 is the schematic lay-out of the portion of the gin property which is discussed in this paper. The collocated TSP and PM_{10} samplers were placed downwind from the cotton gin between the module yard and the cyclone banks. This area was observed to be most often in the dust plume as indicated by the dust laden grasses and module covers. Only a PM_{10} sampler was placed on the upwind (south) side of the facility. On the east was a paved road and on the south, a gravel area. There was minimal vehicle traffic during the tests. The cotton gin trash area was also between the gin and the samplers but on the opposite side of the grassy road and on the western portion of the cotton gin, near the bank of cyclones. The western portion was mainly grassland. Wind direction was mainly from the south and blowing directly through the samplers throughout the test period.

Field Sampling Protocol

The samplers were placed in the dust plume just behind the gin in the downwind portion. This location was not at the boundary or property line. Thus, dust concentrations appearing in this report should not be considered representative of the facility's emissions. The samplers were strategically placed to capture as much dust as possible in the downwind area. The filters were changed approximately every 6 hours which was the duration of each test. The gin was operating 24 hours a day and thus the samplers were also run continuously except during the changing of the filters. A total of ten tests were performed and a total of 50 filters were obtained altogether (10 filters per sampler). There were no problems (e.g., clogging, generator or pump breakdown, etc.) encountered in the operation of the low volume samplers during the duration of sampling tests.

Determination of Concentration

The filters collected from the samplers were first placed in an environmental chamber (70 ºF and 35% RH) to acclimatize prior to weighing. Blank filters were weighed in the same manner. The flow meter of each sampler was calibrated before the sampling test. A HOBO shuttle (Onset Computer Corp., Pocasset, MA) was used to download all data after each run while manually recording the pressure drops across the orifice meter using the Magnehelic gauge. These were post processed to ensure that the flows were within an acceptable limit. The PM concentrations were calculated from the net mass of dust collected by the sampler divided by the total volume of ambient air (actual) that went through the filter during the sampling period.

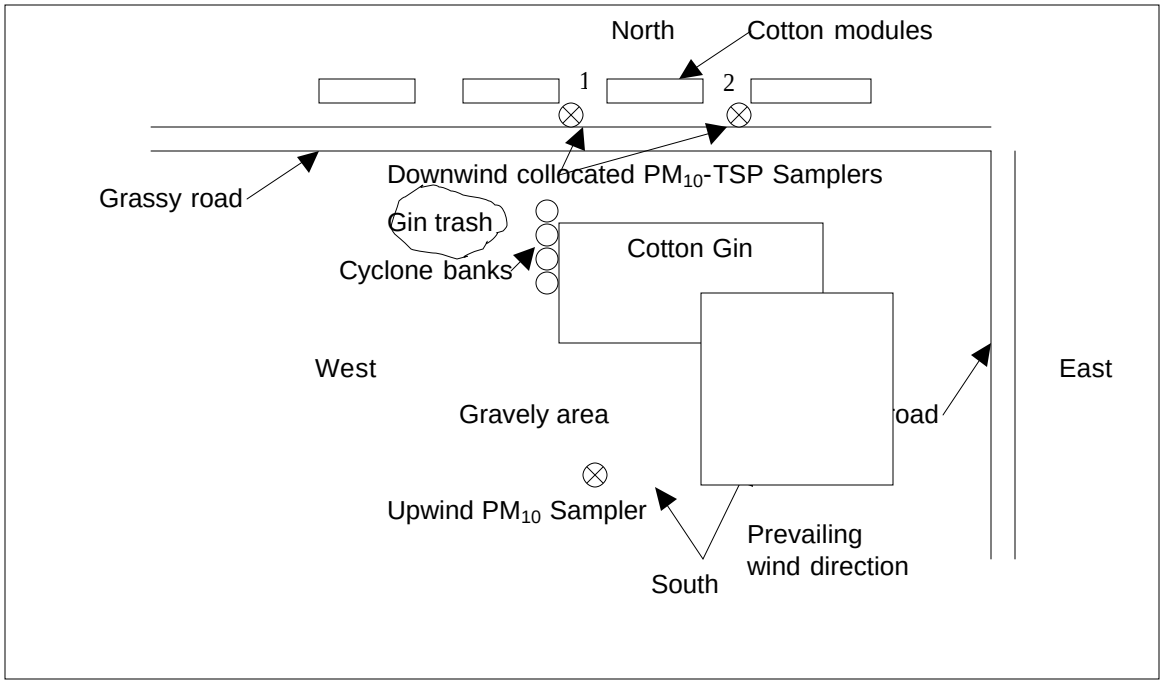

Figure 1. Schematic layout of the area around the cotton gin showing approximate location of samplers.

PSD analysis

The dust particles from the TSP filters were analyzed for particle size distribution using a Coulter Counter Multisizer III (Beckman Coulter, Fullerton, CA). A description of this process has already been presented in a previous paper (Simpson et al. 2003). The dust particles were characterized as to mass median diameter (MMD) and geometric standard deviation (GSD). The particle density of the dust particles was also measured in order to convert the equivalent spherical diameter (ESD) from the Coulter counter method to the aerodynamic equivalent diameter (AED) using the following equation,

$$AED = ESD * \sqrt{\rho_d} \quad (1)$$

where AED = Aerodynamic equivalent diameter
ESD = equivalent spherical diameter
ρ_d = particle density (g/m^3)

The particle size distribution of the collected dust particles was expected to follow a lognormal distribution curve. The parameters in the lognormal distribution include the particle size, the MMD and the GSD. When the particle size distribution is known, the true PM10 concentration from the TSP sampler can be readily estimated. A complete discussion of the principles has been presented in a previous report by Buser et al. (2002).

Results and Discussion

PM10 and TSP Concentrations

Figures 2 and 3 show the PM concentrations obtained from the collocated PM10 and TSP samplers for locations 1 and 2, respectively. The data presented in Figures 2 and 3 correspond to 10 repeated tests in which collocated PM10 and TSP samplers were deployed at two locations downwind from 50 plus-bale-per-hour-capacity cotton gin. In 1 of the 10 tests in Location 1 (Test 4) and 2 out of the 10 tests for Location 2 (Tests 5 and 10), PM10 concentration values exceeded the TSP values (indicated by circling in the figures). Ideally this should not be possible because the cut point for the TSP sampler was 45 µm (captures all PM10 and more) while that of a PM10 sampler was 10 µm. The PM10 concentration should always be lower than the TSP concentration if the sampler is working properly. The only way for the TSP concentration to be lower is when the PM10 sampler is actually capturing large amounts of particles larger than its cut point of

10 µm. Ideally, if both samplers are operating perfectly, the ratio of PM_{10} to TSP should normally be about 50%. There were only three instances in the tests done where the PM_{10} to TSP ratio was at or below 50%. Thus, it appears that for the rest of the time, the PM_{10} sampler was in error and over sampled the PM_{10} concentrations. The design of the pre-collector could be the cause of the errors. The TSP pre-collector has a shrouded cone that prevents the direct entrainment of dust through the filter. The PM_{10} pre-collector does not have a conical shield and the dust guide is horizontal. At high wind speed and high dust concentrations, the PM_{10} sampler pre-collector may be over ridden by dust and larger particles may be entrained easily. The variations in the PM_{10}/TSP ratio throughout the day were a consequence of the wind speed variations and other changing meteorological parameters during the conduct of the test even though the emission rate from the facility remained constant. The other discrepancies from ideal PM_{10}/TSP ratios may be explained by the PSD of the dust on the TSP and PM_{10} filters.

PSD of Typical Cotton Gin Dust

The dusts collected from both the TSP and PM_{10} sampler filters were evaluated for PSD. Figure 4 shows an example of a PSD of the dust collected from the TSP filter (MMD = 11.8 µm and GSD = 2.02 µm, Test No. 3). From the graph, it can be observed that the distribution follows closely a log normal distribution. Thus, by using the MMD and GSD parameter on the lognormal distribution, one should be able to calculate the true PM_{10} concentration. The particle density used in this study was measured and the average value used was 2.12 g/cm^3.

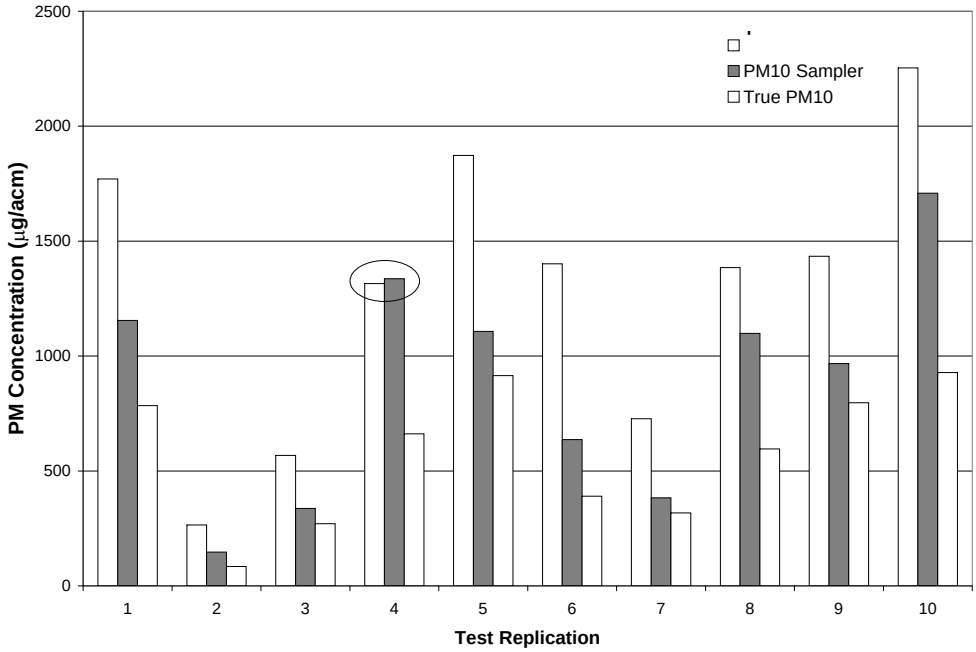

Figure 2. Collocated TSP and PM_{10} sampler concentrations corresponding to samplers positioned at location 1 downwind from a South Texas cotton gin. Circles indicate tests where measured TSP concentration < PM_{10} concentration.

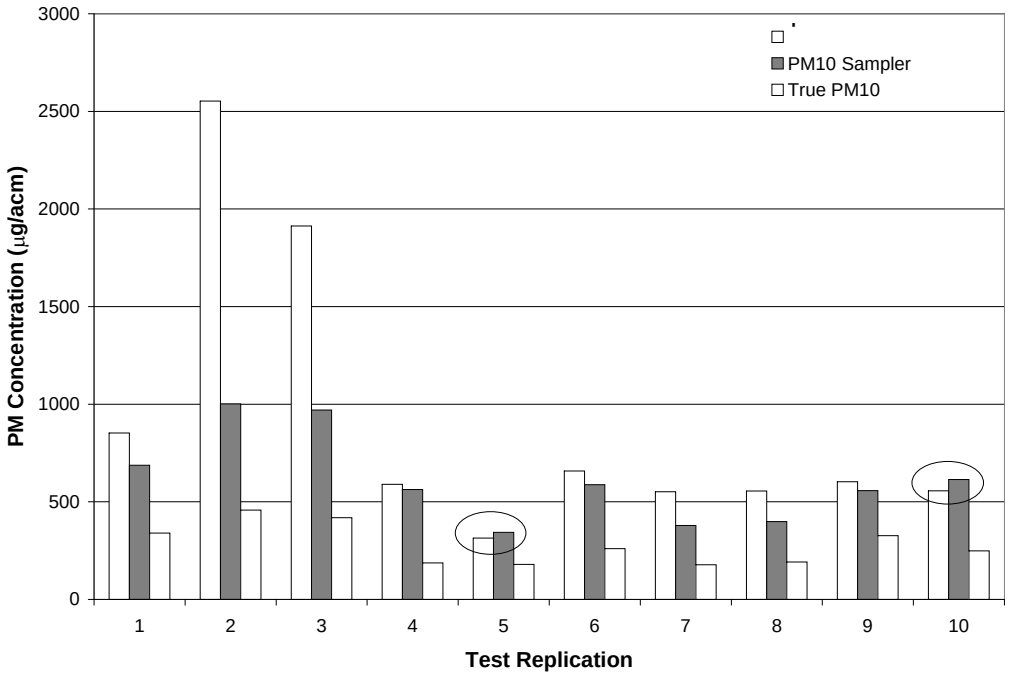

Figure 3. Collocated TSP and PM_{10} sampler concentrations corresponding to samplers positioned at location 2 downwind from a South Texas cotton gin. Circles indicate tests where measured TSP concentration < PM_{10} concentration.

PSD Analysis of Dust in TSP Filters

The MMD values of the gin dust collected from the TSP filters were above 10 µm except on three occasions. The PM_{10} sampler performance was designed based on a cut-point of 10 µm dust. The overall average MMD of dust from the TSP filters was 11.8 $\pm$ 2.25 µm and the GSD was 1.94 $\pm$ 0.16 µm. The true PM_{10} concentration was calculated from these data using the lognormal distribution. The average sampler PM_{10} to TSP concentration ratio was 73.5%. In all instances, the PM concentration from the PM_{10} sampler was in error. This was presumably a consequence of the higher MMD of this particular dust.

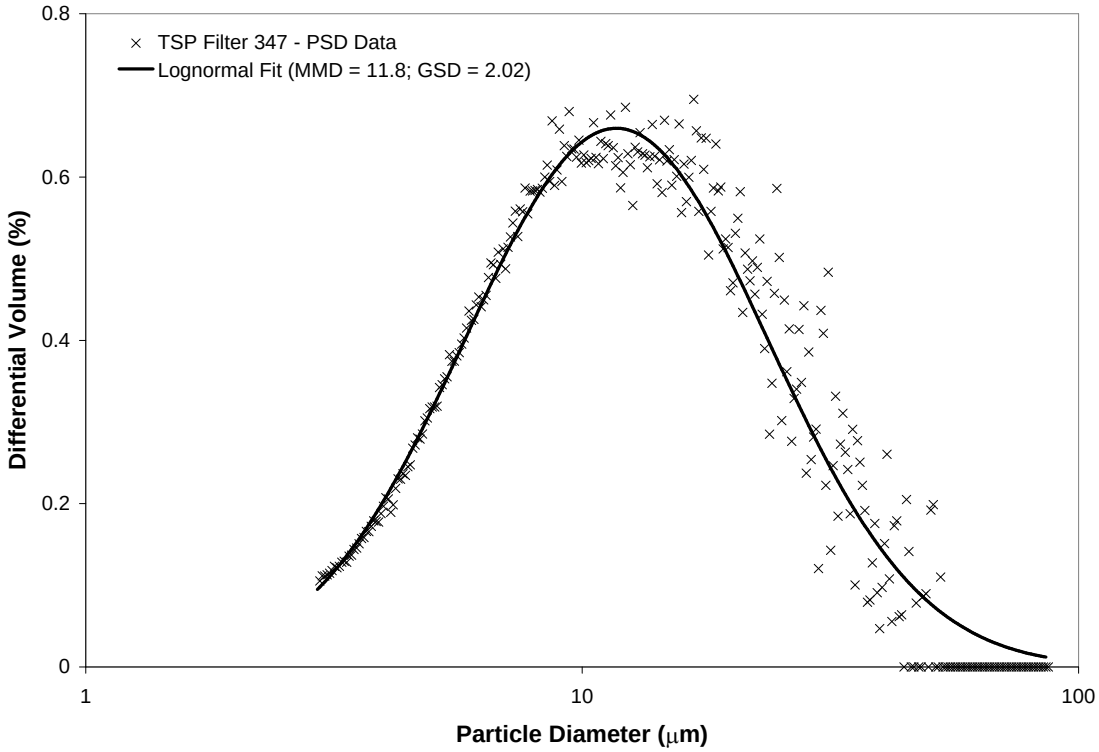

Figure 4. Particle size distribution associated with an exposed TSP filter with a MMD and GSD similar to the average MMD and GSD associated with all TSP filters from locations 1 and 2.

Shown in Figure 5 are plots of concentrations measured by the PM_{10} sampler plotted against PM concentration obtained from the TSP filter for both locations. There was a relatively high degree of linear correlation between both PM concentrations (R^2 = 0.64) giving a sampler PM_{10}/TSP ratio of 62.8%. Figure 6 shows the plot of true PM_{10} from PSD analysis against the TSP concentrations also for both locations. The over sampling for this particular case was more pronounced at very high TSP concentrations. The linear regression equation showed that the true PM10 concentration was approximately 35% of the TSP concentration throughout the range of concentration measured from the yard (R^2 = 0.60).

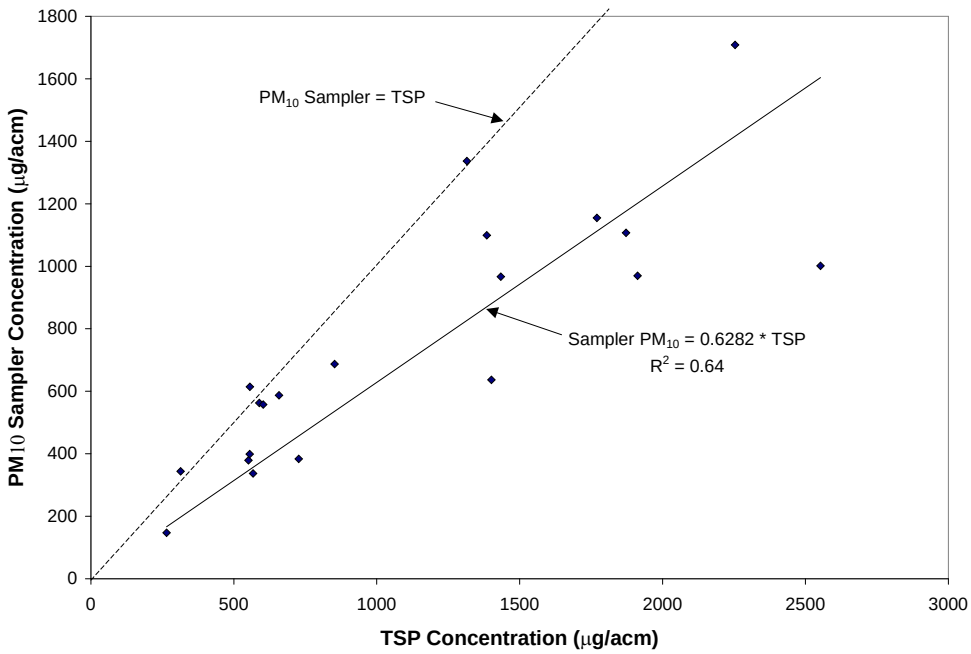

Figure 5. Comparison between the PM_{10} and TSP sampler concentrations obtained from locations 1 and 2 at a South Texas cotton gin.

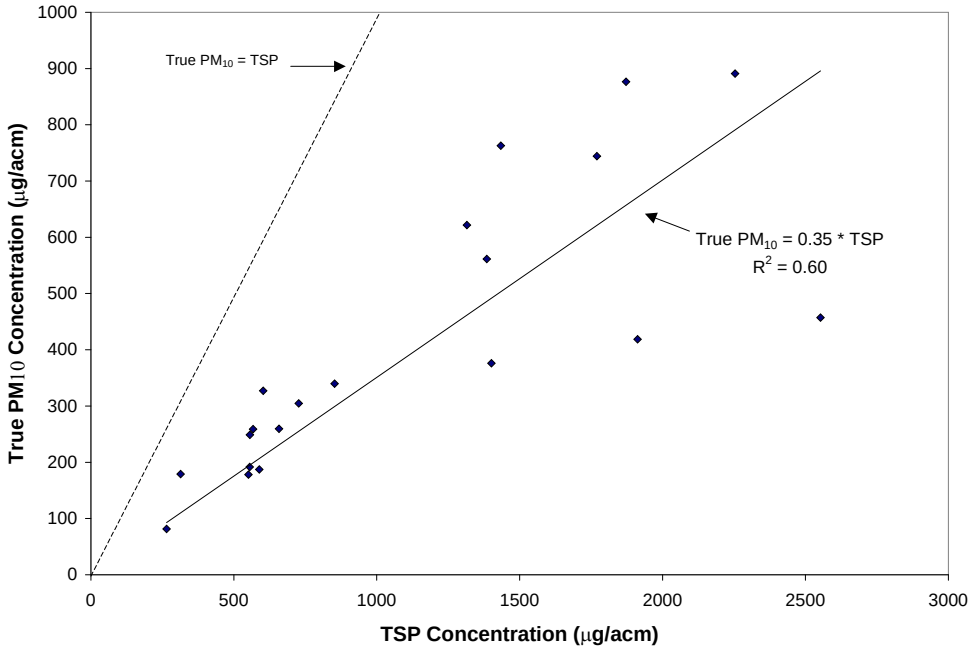

Figure 6. Comparison between the true PM_{10} and TSP sampler concentrations obtained from locations 1 and 2 at a South Texas cotton gin.

PSD Analysis of Dust from PM_{10} Filters

The shift in cut-point for the PM_{10} sampler may be explained partly by the PSD analysis of the PM_{10} filters. Since the average MMD of the dust collected from the PM_{10} filters (10.98 µm in Location 1 and 10.06 µm

in Location 2) was close to that for which the FRM PM_{10} sampler was designed (10 µm), minimal over sampling error was expected. Actual data however showed this was not the case. The GSD of dust from Location 1 was 1.77 µm while that from Location 2 had GSD of 1.76 µm. The ideal GSD of dust particles for the PM_{10} sampler was 1.5 $\pm$ 0.1 µm. The GSD of the dust particles may thus be another factor that contributes to the sampling error.

While the MMD of the PM_{10} filter was close to 10 µm, the measured PM concentrations were higher than expected. One reason may be the broadness of the PSD of this gin dust particles whose GSD was higher than 1.5 µm. Shown in Figure 7 is the PSD of dust particles collected from the PM10 filter with values closest to the mean MMDs and GSDs of all PM_{10} filters. A lognormal distribution fitted curve was superimposed on this graph showing excellent visual agreement.

The above discussions have shown that both the MMD and GSD play a substantial role in the over sampling error of PM_{10} samplers. Even when the MMD of dust collected was very close to 10 µm indicating that over sampling should be small, the over sampling was higher than expected due primarily to the broadness (as against tightness) of the PSD of agricultural dust. The overall MMD for PM_{10} filters was 10.52 $\pm$ 1.88 µm and the GSD was 1.77 $\pm$ 0.07 µm. The interaction of both the MMD and GSD should be taken into account when correcting for the over sampling bias of PM_{10} samplers.

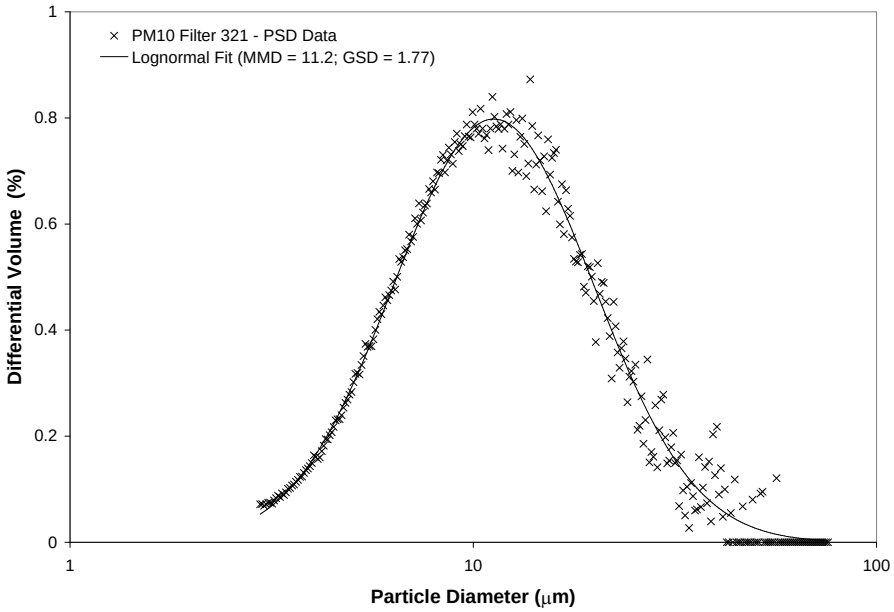

Figure 7. Particle size distribution associated with an exposed PM_{10} filter with a MMD and GSD similar to the average MMD and GSD associated with all PM_{10} filters from locations 1 and 2.

Overall PSD Analysis for both the PM_{10} and TSP Filters

The extent of PM_{10} over sampling may be illustrated by plotting the sampler PM_{10} concentrations against the true PM_{10} concentrations (assumed to be those from the PSD analysis). This is shown in Figure 8 using data from both locations. The regression analysis shows an excellent fit (R^2 = 0.81). By drawing the ideal 45^o line, the conclusion could be made that the PM_{10} sampler concentration was always in error and, at higher dust concentration, there was a marked increase in the over sampling bias. For PM_{10} concentrations in the range from 200-500 µg/m^3 the over sampling resulted in 164 - 410 µg/m^3 concentrations above the true PM_{10} concentrations. The regression equation shows that 55% of the PM_{10} sampler concentration was considered the true PM_{10} concentrations.

Clearly, the use of the TSP sampler followed by the analysis of the PSD of the sample dust seems to provide more accurate reporting of PM_{10} concentrations for agricultural dusts. The PM_{10} sampler reported over sampling bias through the entire range of concentrations measured from this facility. At lower ambient

PM concentration, the percent error was generally lower and the gap between the true and actual concentration was wider at higher PM concentrations.

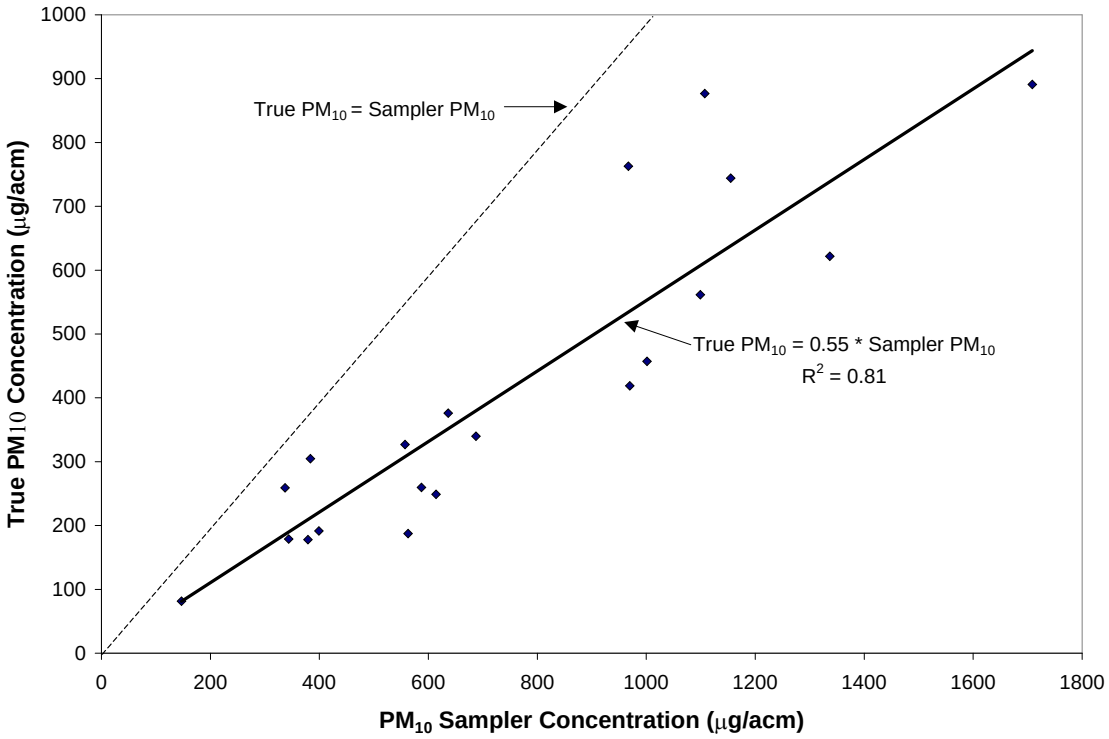

Figure 8. Comparison between the true PM_{10} and PM_{10} sampler concentrations obtained from locations 1 and 2 at a South Texas cotton gin.

Conclusions

TSP and PM_{10} Concentrations

This study has shown that the concentration reported by the PM_{10} sampler was always in error based on the calculation of true PM_{10} concentrations from the PSD analysis of TSP filter catch. Actual field data reported from this study showed that the sampler PM_{10}/TSP ratio was 62.8% and not the ideal 50% from theoretical calculations. The true PM_{10} concentrations from the TSP filters considering the MMD and GSD of dust showed that the PM_{10}/TSP ratio was only 35% throughout the range of concentration measured from this facility. There were instances where the PM_{10} sampler concentration was higher than the TSP concentrations. This would seem impossible, but because of the complexities in the contribution of the shape of the distribution of the dust as described by its PSD, it could be possible. Clearly, the PM_{10} sampler was not suitable for reporting PM_{10} concentrations from agricultural dust whose characteristic particle size was very different from the ideal MMD of 10µm with a GSD of 1.5µm. It was theorized further that this could be a consequence of the pre-collector not performing according to design.

A linear correlation was established for the true PM_{10} calculated from PSD analysis against PM_{10} sampler data from this study. The analysis showed that 55% of the sampler data actually represent the true PM_{10} concentration. This indicated that there was a shift in the cut-point for the PM_{10} sampler, and this should be explored in future work.

PSD Analysis

The PSD analysis showed that when both the dust MMD and GSD differed from 10 µm and 1.5 µm, respectively, over sampling bias from PM_{10} samplers was possible. Even when the dust MMD was close to

the 10 µm value, which was the design value, the error was substantial and this was attributed to the difference in GSD. Other dusts, particularly those with GSD close to 2.0 µm, may behave differently.

This study has revealed new insights on how best to address the PM_{10} sampling bias as follows: (1) There should be a re-evaluation of the inlet head pre-separator for collecting ambient dust samples; (2) The contribution of differing MMD and GSD on the over sampling error must always be considered; (3)Until new and better performing designs of PM_{10} samplers are introduced commercially, more accurate reporting of PM_{10} concentration can be achieved through the use of a TSP sampler followed by the PSD analysis of the dust sample collected.

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