EVALUATIONS OF EPA APPROVED FRM $PM_{2.5}$ AND PM_{10} SAMPLERS

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Abstract

Accurate measurement of particulate matter (PM) concentrations in ambient air is becoming increasingly important as regulatory agencies continue to tighten limits on PM concentrations to which the public may be exposed. However, previous theoretical research has indicated that significant biases are associated with the use of federal reference method (FRM) PM samplers in the presence of large PM such as that generated by many agricultural operations, including cotton gins. Furthermore, field sampling has indicated that sampler performance may be affected by external variables such as dust concentrations, dust characteristics, and wind speed. The objective of this paper is to determine the actual cut-point and slope of two types of EPA-approved FRM PM_{10} samplers using the controlled conditions of a wind tunnel with poly-disperse dusts having varying particle size distributions (PSDs) at different wind speeds and concentrations. For both the PM_{10} inlets analyzed, the cut-points and slopes were not consistently within the acceptable ranges specified by the EPA for FRM PM_{10} samplers. The results of this analysis indicate that these samplers are not operating as intended, and industries may be suffering the consequences of inequitable regulation as a result of sampler error.

Introduction

Accurate measurement of particulate matter (PM) concentrations in ambient air is becoming increasingly important as state and federal regulatory agencies continue to enact stricter limits on PM concentrations to which the public may be exposed. The Clean Air Act of 1970 required the U.S. Environmental Protection Agency (EPA) to develop National Ambient Air Quality Standards (NAAQS) for six criteria pollutants, including PM, on the basis of protecting public health and welfare. Initially PM concentrations were measured in terms of total suspended particulates (TSP), but the NAAQS for PM were revised in 1987 to be based on PM_{10}, which is that fraction of PM having an aerodynamic equivalent diameter (AED) less than or equal to 10 µm (USEPA, 1987). This change from regulating TSP to PM_{10} reflected the purpose of the NAAQS to protect public health.

A challenging issue facing both regulators and industry today is the accurate measurement of ambient PM concentrations. There are numerous articles discussing ambient sampling of the various PM fractions. Chow (1995) summarized some of the sampling errors encountered when using federal reference method (FRM) samplers in a comprehensive paper addressing such topics as minimizing frequency and expense of sampling site visits, appropriate filter media, and the consequences of using samplers for purposes other than that for which they were designed. McMurry (2000) discussed the difficulty of accurately quantifying particle sizes due to particle water content, volatilization, and adsorption to filter media. Wilson et al. (2002) summarized numerous aspects of outdoor PM sampling, including a discussion of the design of different dust indicators and the importance of separation of fine-mode (2.5 µm) and coarse-mode (10-2.5 µm) particles. Faulkner et al. (2007) and Buser et al. (2007) documented systematic errors associated with the use of FRM size-selective PM samplers, particularly the over-sampling biases seen when sampling PM characterized by particles larger than the cut-point of the sampler pre-separator (10- and 2.5-µm for PM_{10} and $PM_{2.5}$ samplers, respectively). Ono et al. (2000) demonstrated that sampler performance may change for certain samplers under heavy loading. Many of these adverse sampling conditions, including sampling of larger particles and operation under heavy PM loading, listed above are encountered when determining emissions from agricultural operations, including those from cotton harvesting and ginning, and could potentially affect the equity with which an industry is regulated.

Measurement of PM_{10} is performed using EPA-approved FRM samplers. A sampler is designated as FRM for PM_{10} measurement if it meets the requirements specified in 40 CFR, Part 50, Appendix J (CFR, 2006b). FRM size-selective samplers have a pre-separator inlet that is used to allow particles of the desired size to be captured on a filter and to prevent unwanted particles from reaching the filter. A sampler's pre-separator performance is measured

using a fractional efficiency curve (FEC), which is characterized by a cumulative lognormal probability distribution with a cut-point (d_{50}) and a slope. The cut-point of a sampler is the particle diameter at which 50% of the PM penetrates the pre-separator and is deposited on the filter, and 50% is captured by the pre-separator (Hinds, 1999). EPA specifies a cut-point of 10±0.5 µm for PM_{10} samplers (CFR, 2006a).

A sampler's slope is defined as the ratio of the particle diameters corresponding to cumulative collection efficiencies of 84.1% and 50% ($d_{84.1}/d_{50}$), 50% and 15.9% ($d_{50}/d_{15.9}$), or the square root of 84.1% and 15.9% $\left(\sqrt{d_{84.1}/d_{15.9}}\right)$ (Hinds, 1999). An ideal sampler would have a slope of 1.0, but no such sampler exists. Although the EPA does not specify the sampler slope in 40 CFR, Part 53, they present idealized sampler performance curves in tabular form from which the sampler performance slope can be calculated as 1.5±0.1 for PM_{10} samplers (CFR, 2006a).

The FECs of samplers are usually assumed to be constant and independent of particle size. This means that it is assumed that a significant loading of large particles does not affect the pre-separator's collection efficiency for smaller particles. This assumption has been shown to be in error under some conditions (Buser et al., 2007). Concentration data used to generate a sampler's pre-separator collection efficiency curve are typically determined by conducting an array of tests over several mono-disperse particle sizes using known ambient concentrations. An example of the EPA FRM PM_{10} sampler's design efficiency curve is shown in figure 1.

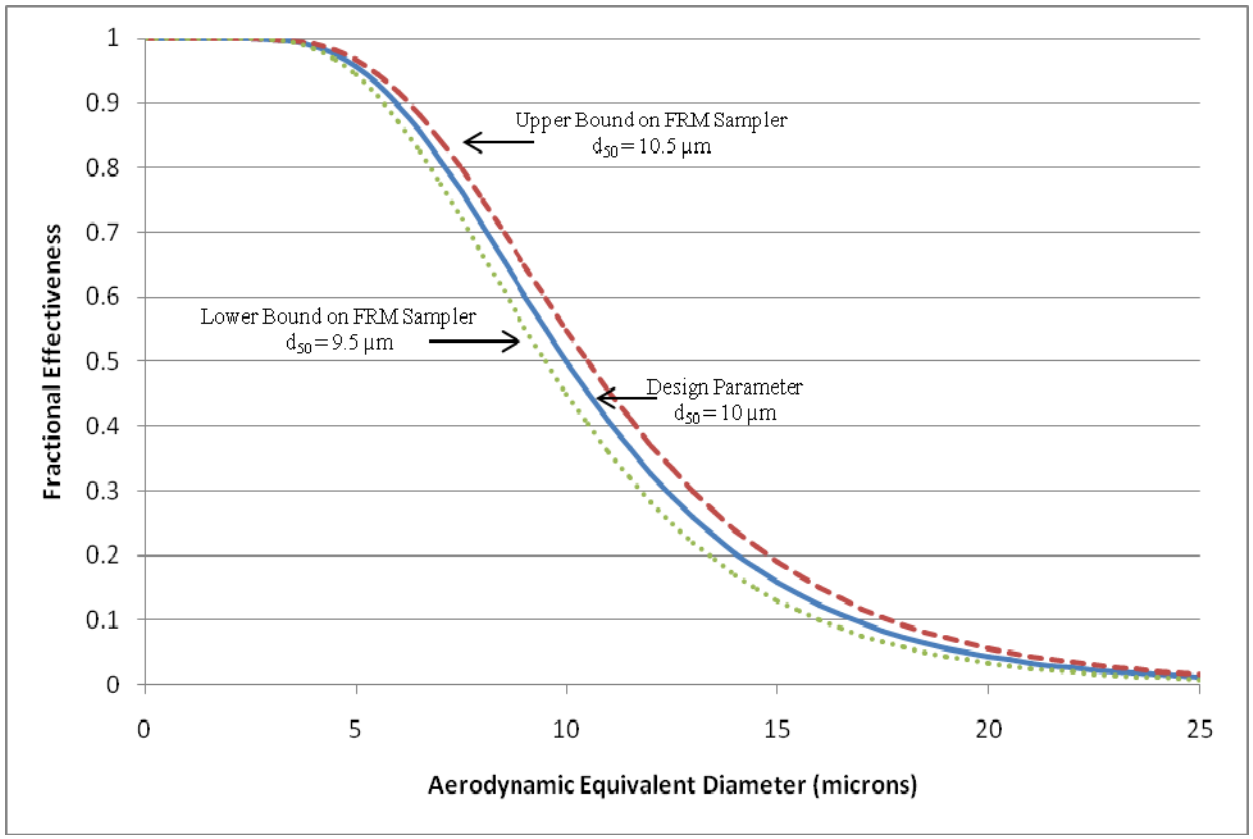

Figure 1. PM_{10} sampler efficiency curve for the FRM guidelines.

If emitting sources of PM are to be regulated equitably, biases and errors associated with the use of FRM samplers must be well understood and accounted for. The objective of this paper is to determine changes in the cut-point and slope of two types of EPA-approved FRM PM_{10} samplers using the controlled conditions of a wind tunnel with poly-disperse dusts having varying particle size distributions (PSDs) at different wind speeds and concentrations. This research explored if, and under what conditions, these FRM PM_{10} samplers perform as specified by the EPA. The over- or under-sampling of these FRM PM_{10} samplers was determined by comparing the concentrations

measured by the FRM PM_{10} samplers to the concentrations determined using a collocated isokinetic sampler and particle size analysis.

Methods

The wind tunnel used in this study conformed to EPA wind tunnel performance standards for uniformity of wind velocity and dust concentration specified in the Title V document of the Clean Air Act Amendments of 1987 (EPA, 1987) and 40 CFR Part 53, Subpart D (CFR, 2006c) (table 1).

Table 1. EPA requirements for the performance of wind tunnels for evaluating PM_{10} samplers.

Parameter		PM_{10} Requirement
Air Velocity	Uniformity	±10% for 2-, 8-, and 24-kph
	Measurement	1) Minimum of 12 test points 2) Monitoring techniques: precision ≤ 2%; Accuracy ≤ 5%
Dust Concentration	Uniformity	±10% of the mean
	Measurement	No less than five evenly spaced isokinetic samplers The sampling zone shall have a horizontal dimension not less than 1.2 times the width of the test sampler at its inlet opening and a vertical dimension not less than 25 cm
Particle Size	Measurement	Accuracy ≤ 0.15 µm; Size resolution ≤ 0.1 µm

This wind tunnel was designed and fabricated by researchers at the Center for Agricultural Air Quality Engineering and Science (CAAQES) at Texas A&M University. An overhead view of the wind tunnel is shown in figure 2. The centrifugal fan (1) (PLR206, New York Blower Company, Willowbrook, IL) was equipped with a variable frequency drive to regulate the speed of the fan. The wind tunnel body was located on an elevated platform to minimize vibration effects. The fan blew air up through a vertical transmission duct which led to a horizontal pre-mixing duct (2). The transition box (3) functioned as an elbow to increase turbulence while the dust feeder (WDF-II, BGI Inc., Waltham, MA) was installed on top of the inflow duct (4). The feed point was such that the dust entered the chamber counter to the air flow to enable turbulent mixing. The inflow duct opened out to the Generic Tee Plenum Systems (GTPS) mixing chamber (5). The air coming out of the GTPS chamber passed through the flow-stabilizing duct (6) where the air flow was stabilized to ensure uniform velocity across the entire cross-section of the sampling plane. At the end of this duct was the test chamber (7), which had an expanded cross-sectional area to avoid wall effects and to permit testing of multiple PM samplers simultaneously. The air coming out of the test chamber passed through a 90º exhaust elbow (8) which directed the flow out through an exhaust fan on the roof (9).

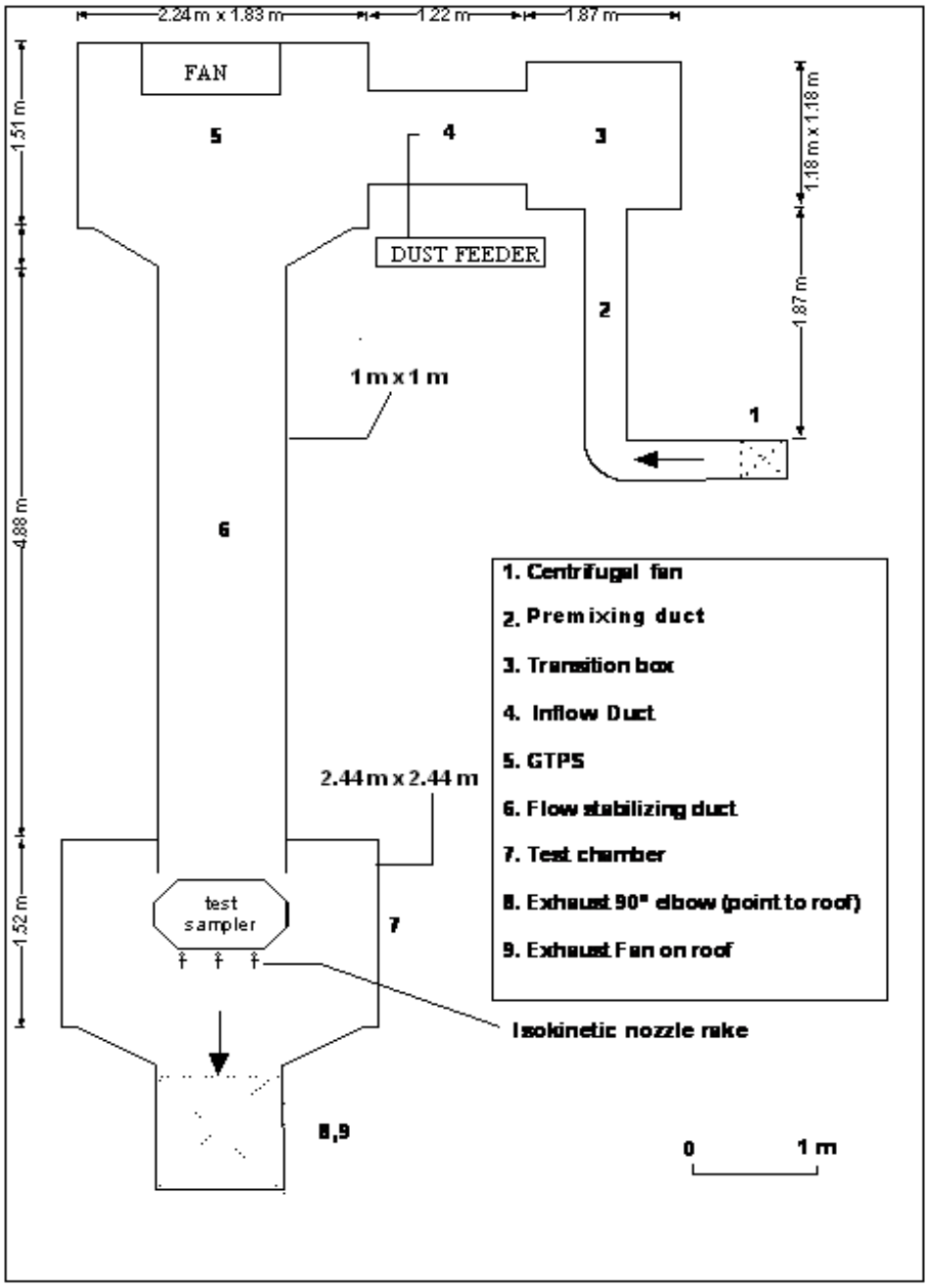

Figure 2. Schematic of the wind tunnel.

The velocity in the sampler test chamber of the wind tunnel was measured using an air velocity transducer (Model 8455, TSI Inc., Shoreview, MN) with a precision of 0.01 m/s and an accuracy of ±0.5% of full scale of the selected range. PM sampling tests were carried out in the presence of poly-disperse dusts as opposed to the mono-disperse dusts used in EPA wind tunnel tests (Ranade et al., 1990). Poly-disperse dusts were used because they are representative of the dusts encountered when sampling ambient PM in the field. Typical urban PM has a mass median diameter (MMD) around 5.7 µm (USEPA, 1996) while agricultural dusts, including dust emitted by cotton gins, have MMDs ranging from 15 to 25 µm (Faulkner et al., 2007). Three dusts were selected for use in this study based on their MMD and geometric standard deviations (GSD) values (table 2).

Table 2. Dusts used for sampler evaluation.

Dust	MMD (µm AED)	GSD
Ultrafine ARD*	5.27	1.63
Fine ARD*	12.05	1.72
Corn Starch	17.14	1.51

*ARD = Arizona Road Dust

The purpose of this study was to evaluate the performance of two types of PM_{10} sampler inlets, namely the Graseby Andersen PM_{10} inlet (henceforth, the flat-head PM_{10} inlet) (SA246B, Thermo Andersen, Smyrna, GA) and the BGI PM_{10} inlet (henceforth, the louvered-head PM_{10} inlet) (P/N PQTSP, BGI Inc., Waltham, MA). The systems used to establish and control the flow rate of the PM_{10} samplers were identical and are described in detail by Buser et al. (2008).

An isokinetic sampling system was used as a reference sampler to ensure that the PM sampled from a moving air stream was representative of the PM of concern in terms of concentration and PSD. The isokinetic sampling system consisted of conical sampling inlets machined from aluminum with inlet nozzle diameters of 19.8-, 10.2-, and 7.4-mm for the three test wind speeds of 2-, 8-, and 24-kph, respectively. The inlets fit onto a 47 mm filter holder which was then attached to an isokinetic probe and installed in the same vertical plane as PM_{10} samplers. Air entering the inlet was drawn through a pump (M161-AT-AA1, Air Dimensions Inc., Deerfield Beach, FL). The air passed through the mass flow controller (MFC) (FMA5420-12VDC, Omega Inc., Stamford, CT) which controlled the air flow rate and adjusted automatically against decreased air flow caused by loading of the filters, keeping the flow rate constant at 1 m^3/h.

PM concentrations were determined according to equation 1.

$$C = \frac{m}{V} \tag{1}$$

where: C = ambient PM concentration ($\mu g/m^3$),
m = mass of PM deposited on the filter during a given test (µg), and
V = volume of air pulled through the filter during a given test (m^3).

To determine the mass of PM deposited on the 47-mm Teflon filters used in the samplers, filters were weighed before and after sampling using a 10 µg resolution scale (AG245, Mettler Toledo, Greifensee, Switzerland). For quality control purposes, filters were conditioned for a minimum of 24 hours before weighing, and each filter weight was an average of three balance readings. If the standard deviation of the three readings exceeded 30 µg, the filter was re-weighed. The volume of air sampled during each test was determined by integrating the volumetric flow rate of air through the system as determined by a calibrated office meter over the total sampling time for a given test. The volumetric flow rate of air through the system was calculated using equation 2.

$$Q = 3.478(K)D_o^2\sqrt{\frac{\Delta P}{\rho_a}} \tag{2}$$

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

The PSD of the PM deposited on all filters was determined using a Malvern Mastersizer (Hydro SM2000, Malvern Instruments Ltd., Worcestershire, UK). Dust-laden filters were immersed into an ethanol electrolyte which was placed into an ultrasonic bath for 15 minutes. The solution was then filtered through a 100 µm screen to remove agglomerated particles. The strained electrolyte/particulate solution was injected into a container of electrolyte from

which a sample was drawn and which was stirred at 1250 rpm. For every PSD analysis, three replications were conducted for all filters, and the average of the three PSDs was analyzed. The PSDs were converted from equivalent spherical diameter (ESD) to AED using equation 3. A shape factor of 1.4, which represents an angular particle, was used for both Ultrafine and Fine Arizona Road Dust (ARD), while a shape factor of 1.05, which represents a more spherical particle, was assumed for cornstarch. The particle densities were determined using a pycnometer (AccuPyc II 1330, Micromeritics, Norcross, GA) and were found to be 2.7 g/cm^3 for both Ultrafine ARD and Fine ARD and 1.5 g/cm^3 for cornstarch.

$$AED = ESD \times \sqrt{\frac{\rho}{\rho_W \times \chi}} \tag{3}$$

where: ρ = particle density (g/cm^3),
χ = particle shape factor (dimensionless), and
ρ_w = density of water (g/cm^3) = 1 g/cm^3

The PM_{10} sampler inlets and the isokinetic sampler inlet were placed in the same vertical plane in the test chamber. The position of the sampler inlets in the test chamber was randomized for each test, while the isokinetic sampler inlet remained in the center as shown. Tests were conducted at wind speeds of 2-, 8-, and 24-kph with PM concentrations of 150-, 300-, 500-, 1000-, and 1500-µg/m^3 for each wind speed. A randomized complete block design with replication as the blocking factor was used. Three replications were conducted.

Sampler performance curves were determined using the protocol from Buser et al. (2008) and Wanjura et al. (2005b) described herein:

The particle size distribution of the PM collected on the filters was represented by a lognormal distribution characterized by a MMD and GSD (Hinds, 1999). The GSD describes the uniformity of the distribution and was calculated according to equation 4.

$$GSD = \sqrt{\frac{d_{84.1}}{d_{15.9}}} \tag{4}$$

where: d_x = the particle diameter for which x percent of the PM mass is less than in diameter.

The lognormal mass density function is expressed by equation 5.

$$f(d_p, MMD, GSD) = \frac{1}{d_p \ln GSD \sqrt{2\pi}} \exp\left[\frac{-(\ln d_p - \ln MMD)^2}{2(\ln GSD)^2}\right] \tag{5}$$

where: d_p = particle diameter (µm).

The percent mass between two particle diameters (a and b) can be determined by integrating equation 5 between the two given particle diameters (eq. 6).

$$f_{a,b}(a, b, MMD, GSD) = \int_a^b f(d_p, MMD, GSD) dd_p \tag{6}$$

Equation 7 expresses the lognormal collection efficiency density function.

$$FEC(d_p, d_{50}, slope) = \int \frac{1}{d_p \ln(slope)\sqrt{2\pi}} exp\left[\frac{-(\ln d_p - \ln[d_{50}])^2}{2(\ln[(slope)])^2}\right] \tag{7}$$

where: FEC(d_p, d_{50}, slope) = fractional efficiency curve of the PM sampler for particle diameter d_p.

The efficiency of an FRM sampler to collect particles of a given size on the filter is described by the sampler penetration curve. The penetration efficiency of particles from 0 to a µm in diameter is given by equation 8.

$$P_m(a, d_{50}, slope) = 1 - \int_0^a FEC(d_p, d_{50}, slope)\,dd_p \quad (8)$$

where: $P_m(a, d_{50}, slope)$ = cumulative penetration efficiency of particles between 0 and a µm in diameter.

The particulate mass concentration of a size-selective FRM PM sampler filter can be determined by combining equations 5 and 8 into equation 9.

$$C_{samp} = C_{amb} \int_0^{\infty} \left(f_{amb}(d_p, MMD, GSD) \times (1 - FEC_{samp}(d_p, d_{50}, slope))\right) dd_p \quad (9)$$

where: C_{samp} = mass concentration on a PM sampler filter,
C_{amb} = ambient PM concentration,
$f_{amb}(d_p, MMD, GSD)$ = particle size distribution of the ambient PM, and
$FEC_{samp}(d_p, d_{50}, slope)$ = fractional efficiency curve of the PM sampler.

The particle size distribution of the PM on a filter from a size-selective PM sampler is related to the ambient PSD and the sampler penetration efficiency curve as shown in equation 10.

$$\int_0^a f_{samp}(d_p, MMD, GSD)\,dd_p = \int_0^a \left(f_{amb}(d_p, MMD, GSD) \times \left(1 - FEC_{samp}(d_p, d_{50}, slope)\right)\right) dd_p \quad (10)$$

where: $f_{samp}(d_p, MMD, GSD)$ = particle size distribution of PM on sampler filter.

Assuming that the ambient concentration and particle size distribution in equations 9 and 10 could be represented by the isokinetic filter concentrations and particle size distributions, equations 11 and 12 were developed from the relationships shown in equations 9 and 10.

$$J = \int_0^{\infty} \left(f_{iso}(d_p, MMD, GSD)\left(1 - FEC_{samp}(d_p, d_{50}, slope) - f_{samp}(d_p, MMD, GSD)\right)\right) dd_p \quad (11)$$

$$K = \frac{C_{samp}}{C_{iso}} - \int_0^{\infty} \left(f_{iso}(d_p, MMD, GSD) \times \left(1 - FEC_{samp}(d_p, d_{50}, slope)\right)\right) dd_p \quad (12)$$

Mass concentrations and PSDs for the isokinetic and PM_{10} samplers were measured as described above. To determine the remaining unknown parameters (i.e. d_{50} and slope of the samplers), J and K from equations 11 and 12 were simultaneously minimized. This process of simultaneously solving equations 11 and 12 for the sampler performance characteristics is referred to as the sampler performance characteristic estimation process. The constraints applied during minimization of differences were: cut-point (upper limit = 200 µm, lower limit = 1 µm) and slope (upper limit = 20, lower limit = 1). This methodology was used to determine the "best fit" cut-points and slopes for both of the PM_{10} samplers used in this study.

Analysis of variance (ANOVA) tests were conducted using the General Linear Model function in SPSS (SPSS 16.0; SPSS, Inc.; Chicago, IL) with an error level of $\alpha = 0.05$ and a null hypothesis stating that the means of either the cut-point or the slope are equal for both PM_{10} samplers used in this study. Means were compared using the Least Significant Difference (LSD) pair-wise multiple comparison test. Independent samples t-tests ($\alpha = 0.05$) were used to compare the measured values for cut-point and slope to the closest maximum or minimum value of the EPA standards of 10±0.5 µm and 1.5±0.1, respectively.

Results and Discussion

The results of the independent samples t-tests comparing the measured cut-point of the two types of PM_{10} samplers used to the EPA standards are shown in table 3. The shaded sections indicate the dust types that yielded cut-points

that are statistically different from the EPA standards. It is important to note that while the means in table 3 may be within the EPA standards for cut-point of 10±0.5 µm, the ranges of values measured were outside the EPA standards.

Table 3. Cut-point values from the flat and louvered PM_{10} samplers separated by dust type.

	Flat PM_{10}			Louvered PM_{10}		
Dust	Mean Cut-Point* (µm)	t-test test value (α = 0.05) (µm)	p-value	Mean Cut-Point* (µm)	t-test test value (α = 0.05) (µm)	p-value
Ultrafine ARD	13.6 ± 1.2	10.5	<0.0005	13.6 ± 1.2	10.5	<0.0005
Fine ARD	9.1 ± 1.3	9.5	0.572	8.3 ± 1.2	9.5	0.045
Cornstarch	10.8 ± 1.4	10.5	0.677	11.2 ± 1.3	10.5	0.306

*Means are shown with a 95% confidence interval.
Shaded sections indicate dust types that have cut-points that are statistically different from the EPA standards.

As seen in table 3, a clear trend in the cut-points was not observed in this study. In contrast, Wang et al. (2005) found that cut-points increased with decreasing MMDs. However, the tests conducted by Wang et al. (2005) did not cover cases with dusts having MMDs less than the theoretical cut-point of a PM_{10} sampler (10 µm) and included two dusts with nearly equal MMDs (10.58 and 10.38 µm, respectively). These results limit the applicability of the conclusions found in the study conducted by Wang et al. (2005).

The cut-points of the flat and louvered PM_{10} samplers operating in conditions with different wind speeds were compared to the closest extreme value from the acceptable range specified by the EPA as determined by the mean cut-point using independent samples t-tests (α = 0.05). Table 4 shows the results of these t-tests with the shaded sections indicating the wind speeds that have cut-points that are statistically different from the EPA standards. Again, it is important to note that while the means in table 4 may be within the EPA standards for cut-point of 10±0.5 µm, the ranges of values measured were outside the EPA standards.

Table 4. Cut-point values from the flat and louvered PM_{10} samplers separated by wind speed.

	Flat PM_{10}			Louvered PM_{10}		
Wind Speed (kph)	Mean Cut-Point* (µm)	t-test test value (α = 0.05) (µm)	p-value	Mean Cut-Point* (µm)	t-test test value (α = 0.05) (µm)	p-value
2	9.3 ± 1.2	9.5	0.789	9.3 ± 0.96	9.5	0.739
8	12.9 ± 1.4	10.5	0.002	12.8 ± 1.3	10.5	0.001
24	11.6 ± 1.5	10.5	0.168	11.2 ± 1.8	10.5	0.427

*Means are shown with a 95% confidence interval.
Shaded sections indicate wind speeds that have cut-points that are statistically different from the EPA standards.

The cut-points of both the flat and louvered PM_{10} inlets were not affected by ambient PM concentrations. Once analysis was complete for the effect on the cut-point of the inlets by individual variables, such as dust type, wind speed, or dust concentration, ANOVA and Multivariate Analysis tests were was performed for the effects of interaction between these three variables on the cut-point and slope of the inlets. The results of these statistical analyses follow with the shaded sections indicating statistically significant interactions. (table 5)

Table 5. ANOVA and Multivariate Analysis results for interactions between dust type, wind speed, and concentration for cut-point of flat and louvered PM_{10} samplers.

	p-values			
	Flat PM_{10}		Louvered PM_{10}	
Variable	Cut-Point	Slope	Cut-Point	Slope
Dust Type	< 0.0005	0.411	<0.0005	0.044
Wind Speed	<0.0005	0.015	<0.0005	<0.0005
Concentration	0.221	0.317	0.026	0.569
Dust Type * Wind Speed	0.001	0.145	<0.0005	0.892
Dust Type * Concentration	0.472	0.265	0.345	0.016
Wind Speed * Concentration	0.814	0.009	0.612	0.004
Dust Type * Wind Speed * Concentration	0.259	0.113	0.244	0.147

Shaded sections indicate statistically significant interactions between the variables.

For both the flat and louvered PM_{10} inlets sampling Ultrafine ARD and Fine ARD at the slower wind speeds of 2- and 8-kph, there were statistical differences between the cut-points measured. When measuring the cut-point of the PM_{10} inlets sampling cornstarch, there were significant differences in the cut-points at the wind speeds of 2- and 8-kph.

Graphical representations of the cut-points at different wind speeds for the three MMDs of dusts used in this study are shown in figures 4 and 5 for the flat and louvered PM_{10} inlets, respectively. The green (light) section of these graphs represents the values of the cut-point that are within the EPA standards, while the red (dark) sections correspond to cut-point values that do not fall within the EPA-specified values.

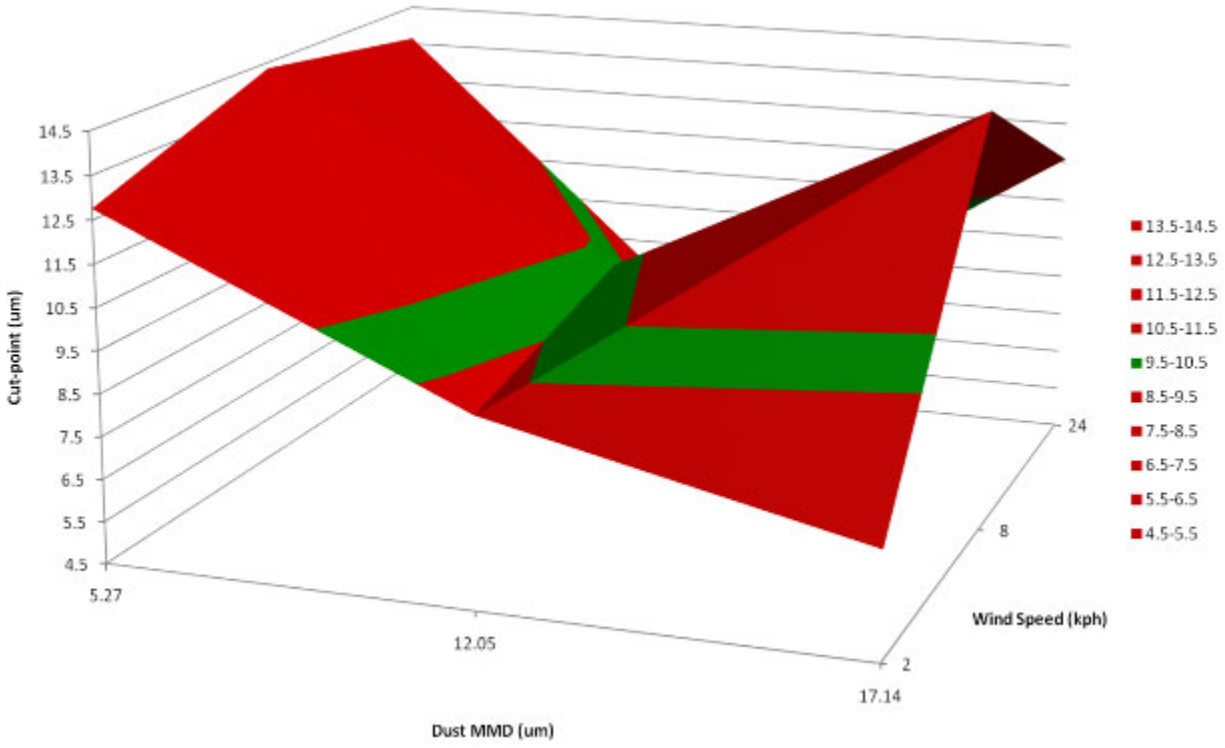

Figure 4. Cut-point values measured for the flat PM_{10} inlet based on wind speed and dust MMD.

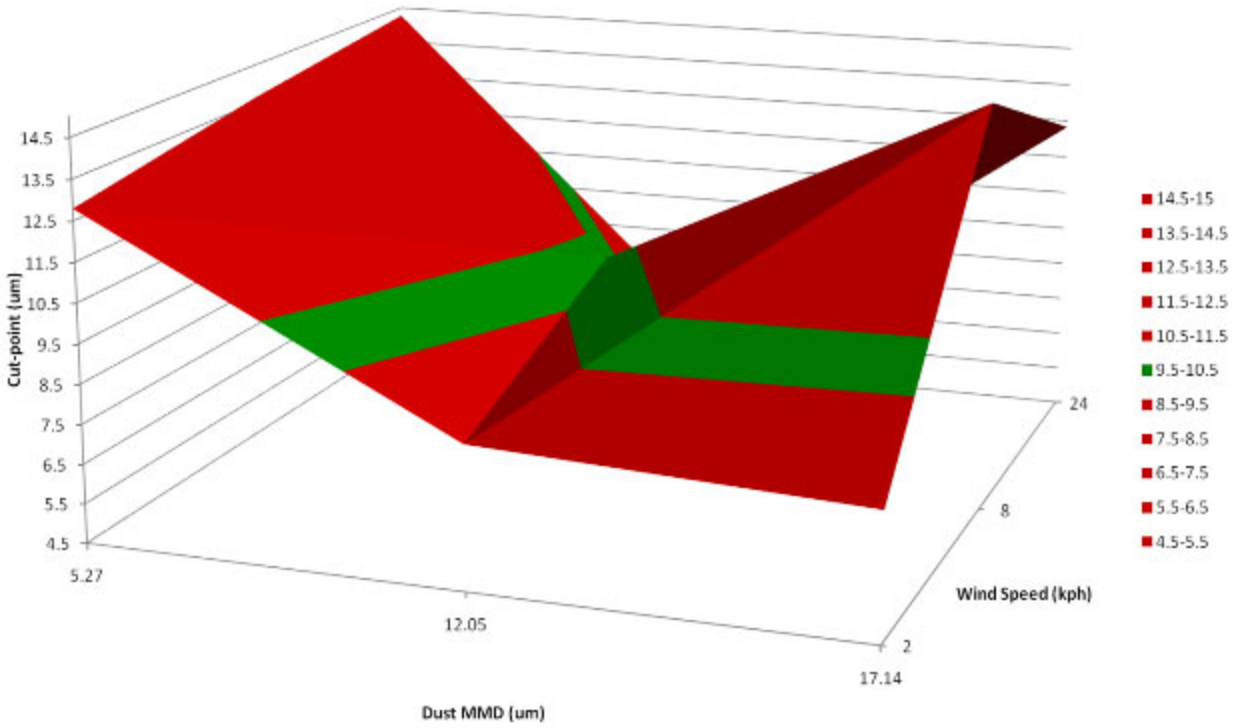

Figure 5. Cut-point values measured for the louvered PM_{10} inlet based on wind speed and dust MMD.

Figures 4 and 5 both show that Fine ARD has a lower cut-point than either Ultrafine ARD or cornstarch at all wind speeds tested with the exception of cornstarch at 2 kph. This is not a result that was expected and will have to be investigated further. Both figures 4 and 5 show that when dust MMD is very small or very large, samplers do not operate as designed. This is an important discovery because if a sampler has a cut-point that is not within the EPA specifications, industries will not be regulated equitably.

Table 6 shows the results of the independent samples t-tests for the flat and louvered PM_{10} samplers comparing the measured values to the EPA standards. The shaded sections of the tables indicate slopes that are statistically different from the EPA standards.

Table 6. Slope values from the flat and louvered PM_{10} samplers separated by wind speed.

	Flat PM_{10}			Louvered PM_{10}		
Wind Speed (kph)	**Mean Slope***	**t-test test value ($\alpha = 0.05$)**	**p-value**	**Mean Slope***	**t-test test value ($\alpha = 0.05$)**	**p-value**
2	2.7 ± 0.2	1.6	<0.0005	2.9 ± 0.3	1.6	<0.0005
8	2.4 ± 0.2	1.6	<0.0005	2.4 ± 0.2	1.6	<0.0005
24	2.2 ± 0.3	1.6	0.001	2.5 ± 0.1	1.6	<0.0005

*Means are shown with a 95% confidence interval.
Shaded sections indicate wind speeds that have cut-points that are statistically different from the EPA standards.

Dust type and concentration did not affect the slopes measured by either PM_{10} sampler used in this study.

Based on the results from ANOVA and the Multivariate Analysis shown in table 5, the flat PM_{10} inlet had statistically different ($p \leq 0.031$) values for slope when measuring higher concentrations at any wind speed. The flat PM_{10} inlet also demonstrated statistical differences ($p \leq 0.024$) in the slope values at the different concentrations when operating at the fastest wind speed of 24 kph. A graphical representation of the effects of wind speed and concentration on the slope of the flat PM_{10} inlet can be seen in figure 6. The red (dark) sections of this graph represent values of the slope that are not within the EPA specifications, while the green (light) section shows slopes that are within the EPA specifications.

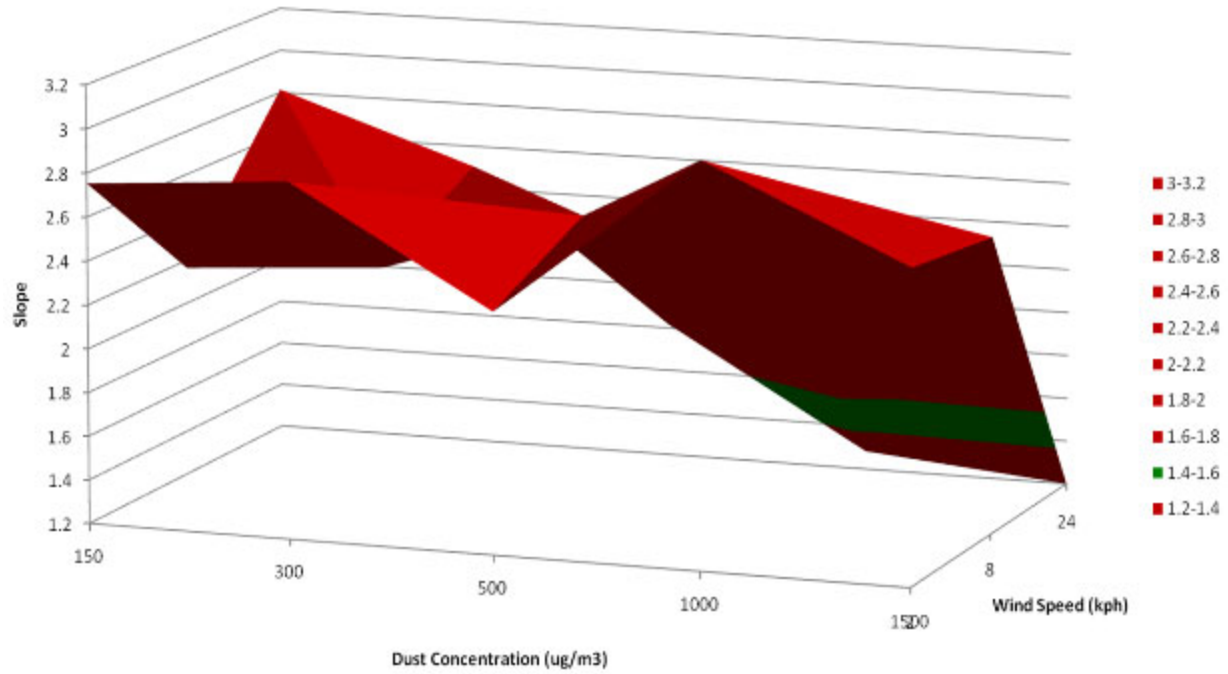

Figure 6. Slope values measured by the flat PM_{10} inlet based on dust concentration and wind speed.

The louvered PM_{10} inlet had a different ($p \leq 0.044$) slope when measuring higher concentrations at both 2- and 24-kph. Higher concentrations also led to a different ($p \leq 0.008$) slope with changes in wind speed for the louvered PM_{10} inlet. These relationships between slope, concentration, and wind speed for the louvered PM_{10} inlet can be seen in figure 7. The entire graph is red (dark), which means that none of the measured slopes were within the EPA specifications.

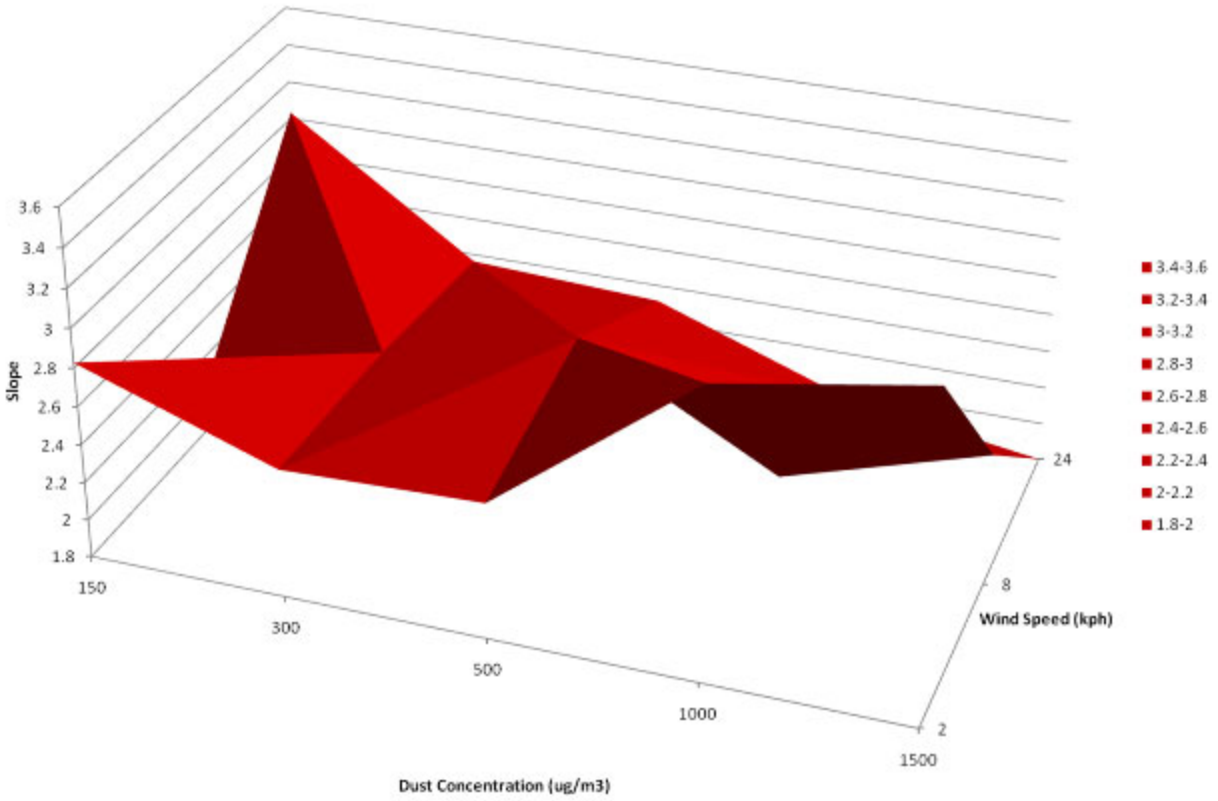

Figure 7. Slope values measured by the louvered PM_{10} inlet based on dust concentration and wind speed.

Figures 6 and 7 show that the slopes of the samplers tested are generally not within the EPA specifications at any combination of concentration and wind speed. The only time that the samplers tested were near the EPA specifications was when the dust concentration was 1500 µg/m^3 and the wind speed was 24 kph. There was little data taken for these conditions, so further research for these conditions may show different results.

These results demonstrate the need for further evaluation of the EPA approved FRM PM_{10} samplers to ensure that all industries are equitably regulated. From the data above, it is clear that both the flat and louvered PM_{10} inlets do not perform as intended when used to sample dust with larger MMDs. This means that agricultural operations, such as cotton harvesting and ginning, may have unnecessary air permitting fees simply because the samplers used to determine their emissions did not accurately measure emission concentrations.

Conclusions

For sources of particulate matter to be regulated equitably, the biases and errors associated with the use of FRM PM_{10} samplers must be accounted for and accurately characterized. For both the flat and louvered PM_{10} inlets, the cut-points and slopes were not consistently within the acceptable ranges specified by the EPA for FRM samplers. The slopes were higher than the maximum value of 1.6 specified by the EPA for FRM PM_{10} samplers for both the flat and louvered PM_{10} inlets at all wind speeds. Many of the cut-point values were higher than the EPA specified maximum value of 10.5 µm when separated and analyzed by both dust type and wind speed with the exception of Fine ARD sampled by the louvered PM_{10} inlet at any wind speed, which was significantly lower than the minimum EPA standard of 9.5 µm. The results of these analyses indicate that these samplers are not operating as they are intended and industries may be suffering the consequences of inequitable regulation based on dust MMD, concentration, and ambient wind speeds. These consequences may include increased regulatory fees being placed on industries with dusts that have higher MMDs such as agricultural operations, including cotton harvesting and ginning.

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