EVALUATION OF PM_{10} AND TOTAL SUSPENDED PARTICULATE SAMPLER PERFORMANCE THROUGH WIND TUNNEL TESTING

A Thesis

by

MARY KATHERINE THELEN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2010

Major Subject: Biological and Agricultural Engineering

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Approved by:

Chair of Committee,	William Brock Faulkner
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ABSTRACT

Evaluation of PM_{10} and Total Suspended Particulate Sampler Performance through Wind Tunnel Testing. (August 2010)

Mary Katherine Thelen, B.S., Texas A&M University

Chair of Advisory Committee: Dr. William Brock Faulkner

Particulate matter (PM) concentrations in ambient air can be monitored by gravimetric sampling near a source using Federal Reference Method (FRM) samplers. PM is regulated by size, with PM_{10}, which is comprised of particles with aerodynamic equivalent diameters less than or equal to 10 μm, being the main focus of this research. FRM PM_{10} samplers exhibit sampling errors when sampling dusts with mass median diameters (MMDs) that are larger than the 10 μm sampler cutpoint. For industries to be regulated equitably, these sampler errors must be quantified and understood.

This research evaluates the performance of FRM PM_{10} and low volume total suspended particulate (TSP) samplers under the controlled conditions of a wind tunnel. The performance evaluation was conducted by observing the sampler cutpoints, slopes, and measured concentrations. These measured values were compared to values obtained using a collocated isokinetic reference sampler.

The results of this research indicate that PM_{10} samplers do not operate as intended under all conditions. The cutpoint of the PM_{10} inlets was significantly higher than the maximum FRM limit of 10.5 μm when sampling dust with MMDs larger than

the cutpoint of the sampler. The slope values for the PM_{10} inlets were significantly higher than the maximum FRM limit of 1.6.

MMDs and geometric standard deviations of PM collected by TSP samplers were significantly different than those of PM collected using the collocated isokinetic sampler. The concentrations measured by the TSP samplers were significantly higher than the collocated isokinetic sampler.

The results of this research provide a better understanding of the performance of TSP and PM_{10} samplers operating under different conditions and shows that these samplers are not operating as intended. Because of this, industries may be suffering the consequences of inequitable regulation.

DEDICATION

To

My Parents

For teaching me the importance of hard work.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Brock Faulkner, for answering all of my questions, crazy or not, and challenging me to always learn. I would also like to thank my committee members, Dr. Parnell, Dr. Lacey, and Dr. O'Neal, for their guidance and support throughout the course of this research.

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Thanks to my parents for everything you have given me to help me succeed in life. I know that you probably grew tired of hearing about my project, but I appreciate the patience and support that you have always shown.

Finally, I would like to extend a very special thanks to Mark for keeping me calm when I thought I would never finish and helping me countless times with "just one more thing before we leave". I look forward to our future together!

NOMENCLATURE

AED	Aerodynamic Equivalent Diameter
ARD	Arizona Road Dust
CAAA	Clean Air Act Amendments
CAAQES	Center for Agricultural Air Quality Engineering and Science
CAFO	Concentrated Animal Feeding Operations
EPA	Environmental Protection Agency
ESD	Equivalent Spherical Diameter
FEC	Fractional Efficiency Curve
FRM	Federal Reference Method
GSD	Geometric Standard Deviation
MMD	Mass Median Diameter
NAAQS	National Ambient Air Quality Standards
PM	Particulate Matter
PSD	Particle Size Distribution
SAPRA	State Air Pollution Regulatory Agencies
TSP	Total Suspended Particulate

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CHAPTER I

INTRODUCTION

Passage of the Clean Air Act Amendments (CAAA) of 1970 was an important environmental legislative action in the United States. The CAAA of 1970 required the Environmental Protection Agency (EPA) to enforce air pollution controls in the United States and required EPA to set National Ambient Air Quality Standards (NAAQS) for pollutants considered harmful to public health and welfare (USEPA, 1996). NAAQS are a two-tiered regulatory standard composed of primary and secondary standards. The primary standards were aimed at protecting public health (especially the health of "sensitive" population groups such as children and the elderly), while the secondary standards were aimed at protecting public welfare, including aesthetic or economic damages. In 1971, EPA promulgated NAAQS for six criteria pollutants known to cause adverse health effects and adopted the primary and secondary standards as the upper limits of permissible pollutant concentrations which, if exceeded, would lead to unacceptable air quality (Federal Register, 1971). The original NAAQS for particulate matter (PM) was set for total suspended particulate (TSP) with the 24-hour primary standard set at 260 $\mu g/m^3$ and the 24-hour secondary standard at 150 $\mu g/m^3$. EPA modified the PM standard several times based on evolving research relating health risks to PM.

The current PM NAAQS regulates two categories of PM: $PM_{2.5}$ and PM_{10},

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This thesis follows the style of *Transactions of the ASABE*.

which are comprised of particles with aerodynamic equivalent diameters (AEDs) less than or equal to 2.5- or 10-μm, respectively (CFR, 2006b). EPA currently uses PM_{10} as an indicator of the concentration of particles with an AED less than or equal to 10 μm but greater than 2.5 μm, known as inhalable coarse particles (PM_c or PM_{coarse}). In 2006, the primary 24-hour PM_{10} standard of 150 $\mu g/m^3$ (99^{th} percentile) was reaffirmed to gather more data about measured PM_c concentrations, which may lead to promulgation of a concentration standard for PM_c in the future. EPA, however, revoked the annual PM_{10} standard as available health evidence did not suggest a substantial link between long-term exposure to PM_{10} and health concerns (CFR, 2006a). The secondary standards of both $PM_{2.5}$ and PM_{10} are equivalent to the primary standards.

PM concentrations in ambient air can be monitored by gravimetric sampling near a source using Federal Reference Method (FRM) samplers. A sampler is designated as FRM under the provisions of 40 CFR, Part 53 (CFR, 2006b). EPA designates those PM_{10} samplers which meet the requirements specified in 40 CFR, Part 53, Subpart D and meet additional specifications set forth in 40 CFR, Part 50, Appendix J (CFR, 2006c) as FRM samplers.

Size selective PM samplers are employed to measure PM_{10} concentrations. A pre-collector is the part of a sampler that separates the particles collected by the sampler by size. A PM_{10} pre-collector is assumed to have performance characteristics that can be described by a cumulative lognormal probability distribution with a cutpoint (d_{50}) and a slope. The cutpoint of a sampler is defined as the particle diameter at which 50 percent of the particles of that size penetrate the pre-collector of the sampler and are deposited

on the filter (Hinds, 1999). The slope of a sampler performance curve is the slope of the lognormal collection efficiency curve of the pre-collector and is defined as the ratio of the particle sizes corresponding to collection efficiencies of 84.1% and 50% ($d_{84.1}/d_{50}$) or 50% and 15.9% ($d_{50}/d_{15.9}$) or the square root of the ratio of $d_{84.1}/d_{15.9}$ (Hinds, 1999). An FRM PM_{10} sampler is required to have a cutpoint of 10 ± 0.5 μm and although a slope value is not specifically stated, idealized sampler performance curves in tabular form are presented from which as slope of 1.5 ± 0.1 can be calculated (CFR, 2001).

A particle size distribution (PSD) is a distribution of particles by volume, mass, or number. The distribution of the particles on a mass basis is the PSD used for regulatory purposes. Most ambient aerosols are represented by PSDs that are lognormal in nature and characterized by a mass median diameter (MMD) and geometric standard deviation (GSD) (Hinds, 1999).

Most size-selective PM samplers rely on a pre-collector inlet that includes an impactor plate that allows particles of a desired size to penetrate the pre-collector and deposit on a filter while preventing undesired particles from penetrating the pre-collector and reaching the filter. These impactors work by rapidly changing the direction of air flow, which causes particles with more inertia to impact onto a plate. The performance of a PM sampler is defined by its fractional efficiency curve, which is the collection efficiency of the sampler. The expected mass density distribution of a sampled aerosol on the sampler filter can be determined using a PM sampler's fractional efficiency curve combined with the idealized ambient PSD (Buser et al., 2007a).

No size selective sampler is capable of allowing 100% of all particles below a given size to penetrate while rejecting 100% of all the particles above that size (Buser et al., 2007a). In addition, impacted particles may bounce, or as the layer of particles on the impaction surface increases, some of the particles may begin to blow off and deposit onto the filter, which may lead to sampling errors.

When sampling with an FRM PM_{10} sampler, some particles larger than 10 µm penetrate the pre-collector and are collected on the filter while some particles smaller than 10 µm are captured by the pre-collector and are not collected on the filter. Hence the term "measured PM_{10}" is nominal since it includes a mass of particles that are larger than 10 µm and excludes a mass of particles smaller than 10 µm (figure 1; Buser et al., 2007a). A common assumption made in the regulatory community is that the mass of particles within the size range of interest captured by the pre-collector is equal to the mass of particles larger than the size range of interest that penetrate the pre-collector and are collected on the filter (CFR, 2006b).

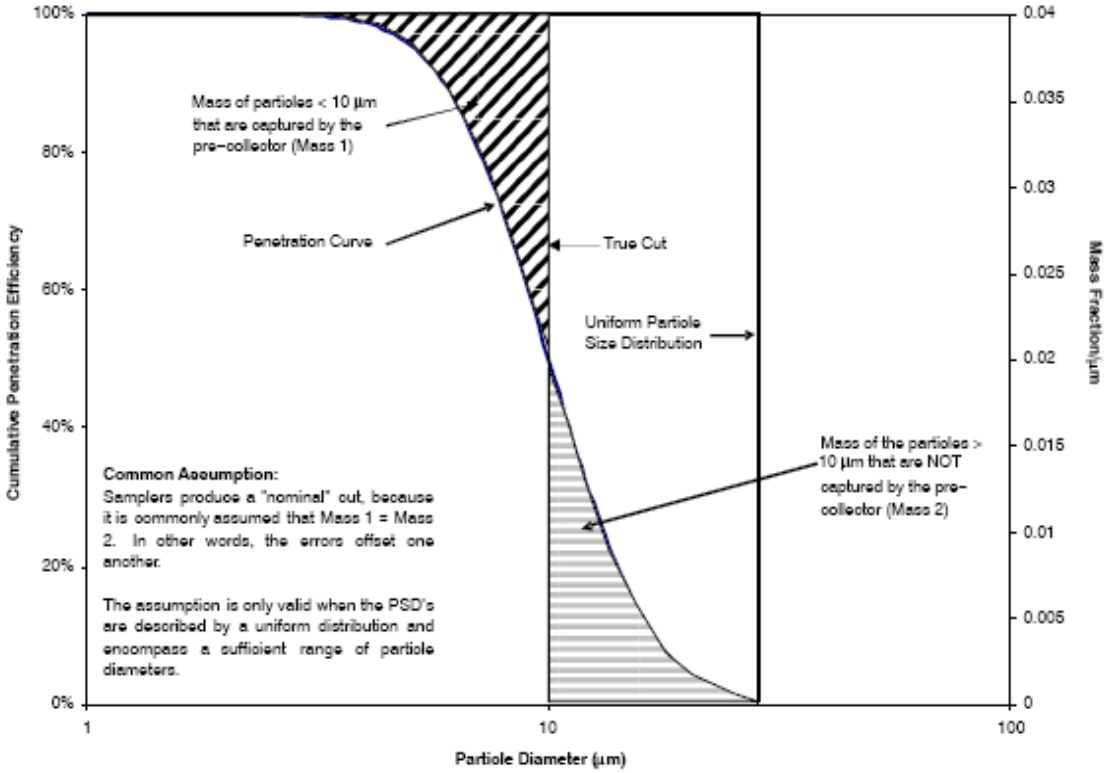

Figure 1. PM_{10} sampler nominal cut for a uniform PSD (Buser et al., 2007a).

Aerosols commonly encountered in urban areas have an MMD that is smaller than the cutpoint of an FRM PM_{10} sampler (USEPA, 1996), which means the mass of particles smaller than 10 µm that does not reach the filter (Mass 1) is greater than the mass of particles larger than 10 µm that penetrates the pre-collector (Mass 2) and reaches the filter. This is a case of FRM PM_{10} sampler under-sampling bias (figure 2).

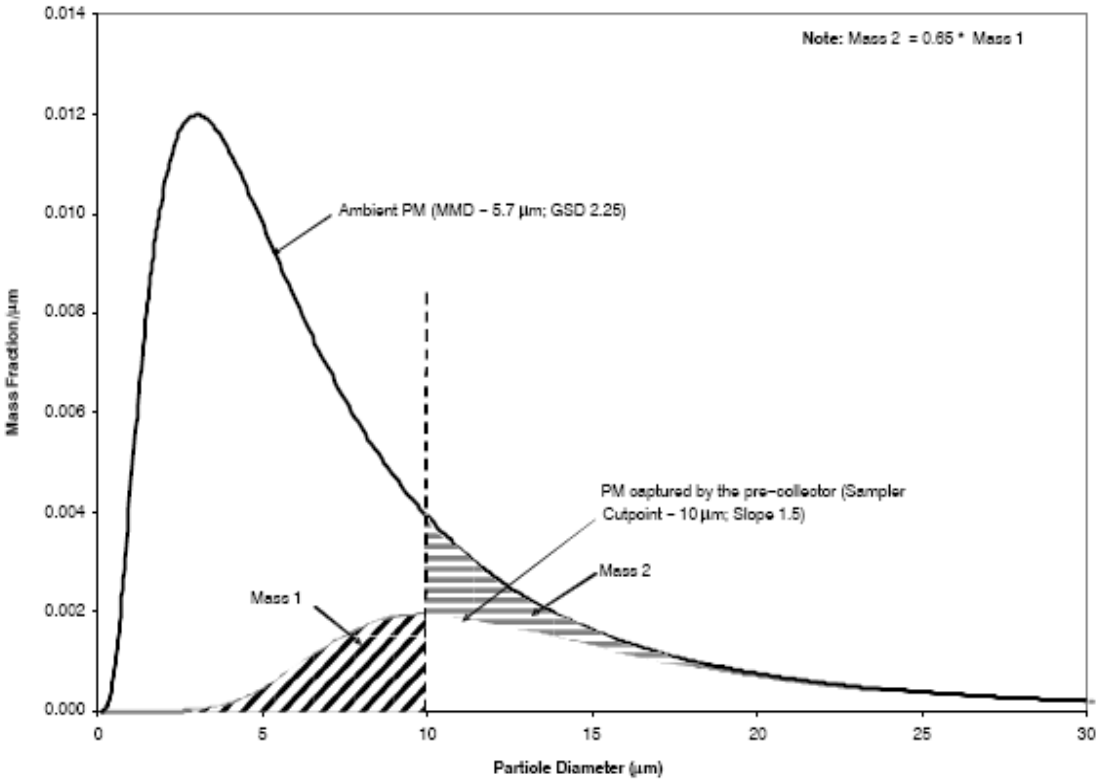

Figure 2. PM_{10} sampler nominal cut for a lognormal PSD with an MMD = 5.7 µm and GSD = 2.25 (Buser et al., 2007a).

When the MMD of the ambient dust being sampled is larger than the cutpoint of the sampler, as is commonly the case in rural areas, the mass of particles smaller than 10 µm that does not reach the filter (Mass 1) is less than the mass of particles greater than 10 µm that penetrates the pre-collector (Mass 2) and is deposited on the filter. In this case, over-sampling of PM_{10} by an FRM PM_{10} sampler occurs (figure 3). As the MMD of the dust in the air and the cutpoint of a sampler diverge, the amount of under-sampling or over-sampling bias increases (Buser et al., 2007b).

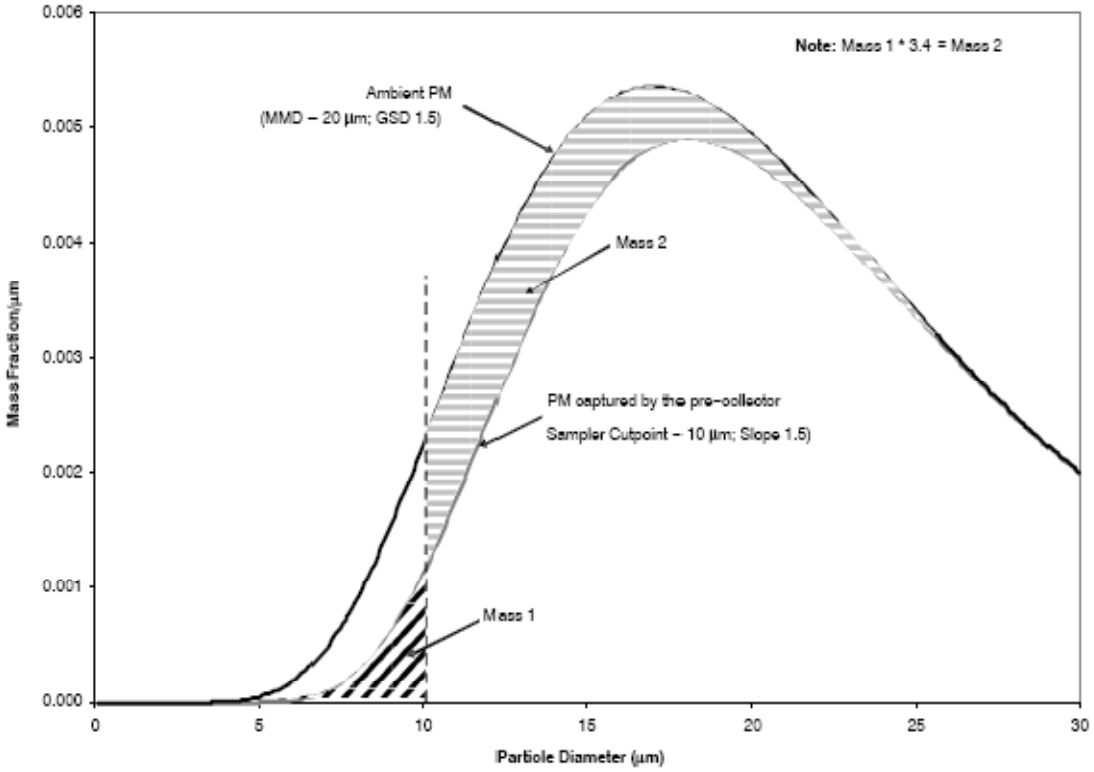

Figure 3. PM_{10} sampler nominal cut for a lognormal PSD with an MMD = 20 µm and GSD = 1.5 (Buser et al., 2007a).

Theoretical analysis has shown that PM_{10} sampler measurements could be 139 percent to 343 percent higher than the true PM_{10} concentration even if the pre-collector operates within FRM performance standards when sampling PM with an MMD of 20 µm and GSDs of 2.0 and 1.5, respectively (Buser et al., 2007b). Using an empirical approach, Wang et al. (2005b) documented an increase in FRM PM_{10} pre-collector cutpoints with decreasing MMD of dusts. Deviations from the EPA-specified range of cutpoints due to fluctuating wind speed and ambient aerosol concentrations have also been reported (Ono et al., 2000). The shift of sampler performance characteristics may lead to additional under- or over-sampling errors when measuring PM concentrations for

regulatory purposes. Additionally, biases in measured concentrations of $PM_{2.5}$ and PM_{10} may lead to compounding of errors and uncertainties when determining PM_c concentrations, which may be an issue for future NAAQS (Federal Register, 2006).

Concentrations of PM_{10} obtained from property line sampling of ambient air using FRM samplers may be incorporated by state air pollution regulatory agencies (SAPRAs) to regulate industries, issue permits, and decide penalties or operating fees. The aforementioned sampler bias issues raise questions about the equity of the methods used for determining regulatory compliance. Until recently, agricultural industries were exempt from a vast number of air quality regulations. This was mostly due to the small size of most of these operations, resulting in these industries being minor sources of PM, and the rural, sparsely populated location of many agricultural industries. But with increasing urban sprawl, many agricultural operations like cotton gins, feed mills, grain elevators, dairy operations, and harvesting operations have become subject to air quality regulations. Furthermore, as urban growth continues to encroach on lands that have historically been used in agricultural production, increasing the proximity of agricultural operations to human dwellings, there is an increasing call for air quality regulations regarding agricultural operations which may emit large quantities of PM. Due to the interaction of PSD and sampler characteristics, existing PM samplers used by SAPRAs and EPA can substantially misrepresent the fractions of particles within the size ranges of interest in agricultural operations. If these erroneous higher concentrations are applied to regulation of agricultural operations, it may place an undue economic burden on many agricultural industries forced to comply with current standards.

While many publications have pointed to problems with federally-approved sampling protocols and samplers (Ono et al., 2000; Wang et al., 2005b), it is difficult to compare the performance characteristics of the samplers in these studies to quantify the shifts in sampler performance because the environmental conditions and the PSD of sampled PM in each case are different and often undocumented. Controlled testing is needed to accurately characterize the performance of various FRM PM samplers operating in the presence of PM characterized by larger particles, as is typical of PM emitted from agricultural industries.

Previous studies have indicated a strong relationship between shifts of cutpoint and ambient wind speeds (Ono et al., 2000) and shifts in $PM_{2.5}/PM_{10}$ concentration ratios towards smaller values have been observed with increasing ambient PM_{10} concentrations (Cowherd, 2005). Such a shift could lead to errors in PM_c calculations. In order to determine the suitability of current regulatory sampling protocol followed by SAPRAs and EPA, effects of variations in wind speed, ambient PM concentrations, and PSDs of aerosols on the performance of FRM PM samplers should be quantified through controlled testing.

Objectives

The goal of this research was to evaluate the performance of FRM PM_{10} and low volume TSP samplers under the controlled conditions of a wind tunnel. The performance evaluation was conducted by observing the sampler cutpoints, slopes, and measured concentrations. Specifically the objectives of this research were:

1. Through theoretical and empirical analysis, investigate how changes in sampler flow rate affect the performance of FRM PM_{10} samplers operating in the presence of poly-disperse PM with various PSDs at different wind speeds.
2. Empirically investigate the performance of two FRM PM_{10} samplers operating in the presence of poly-disperse PM with various PSDs at different aerosol concentrations and wind speeds.
3. Empirically determine if the concentrations and PSDs from testing of low volume TSP samplers can be used for determining true PM_{10} concentrations by performing collocated testing of TSP and isokinetic samplers in the wind tunnel.

CHAPTER II

LITERATURE REVIEW

The results of PM sampling determine whether an area or a source meets EPA and state regulatory standards for PM. Therefore, the PM collected by FRM samplers should be representative of the aerosols present in the ambient air around the sampler. A number of studies have investigated the performance characteristics of FRM samplers under various field conditions.

Wang et al. (2005b) carried out sampling tests with Graseby-Andersen FRM PM_{10} samplers in presence of cornstarch, fly ash, and alumina by collocating them with low volume TSP samplers in a test chamber. The authors found that the PM_{10} samplers over-sampled when exposed to ambient PM having MMD values larger than 10 μm AED, and under-sampled when exposed to ambient PM having MMD values smaller than 10 μm AED. The authors also reported shifts of performance characteristics, (i.e. cutpoint and slope) indicating that the cutpoint increased as the PM MMD decreased. Wang et al. (2005b), however, reported that there was a considerable horizontal and vertical gradient in the concentrations measured by the TSP samplers in their test chamber, and the authors did not control the wind speed for their tests. These results indicate the need for further testing in the controlled conditions of the wind tunnel.

Buser et al. (2008) used collocated TSP and FRM PM_{10} samplers to monitor dust emissions from a cotton gin in south Texas. The MMD and GSD of the PM collected on the TSP filters were 13.4 ± 1.51 μm and 2.0 ± 0.11, respectively. Calculated ranges of

cutpoint and slope were from 13.8- to 34.5- μm and 1.7 to 5.6, respectively, which resulted in overestimation of true PM_{10} concentrations by 145 percent to 287 percent.

There is little literature pertaining to wind tunnel testing of samplers. EPA wind tunnel (Ranade et al., 1990) and most other wind tunnel studies (McFarland and Ortiz, 1982) were for either design modification of existing FRM samplers or evaluation of sampler performance. These studies used mono-disperse liquid or solid aerosols to determine the collection efficiency of PM samplers for aerosols of a specific size. Wind tunnels have also been used to evaluate candidate samplers for FRM designation (McFarland et al., 1984; Wedding et al., 1985). Chen (2007) designed and fabricated a controlled environment sampler testing wind tunnel meeting EPA requirements for velocity profile and PM concentration uniformity as listed in Title V of the Clean Air Act (USEPA, 1987) and 40 CFR, Part 53, Subpart D (CFR, 2006b).

Rationale and Significance

Previous EPA wind tunnel tests were primarily focused on characterizing the performance of candidate samplers for purposes of FRM designation (Ranade et al., 1990). The effect of varying aerosol concentrations on sampler performance was not determined in EPA tests. Wind tunnel testing, for the purpose of this research, permitted simulation of agricultural and urban conditions through the selection of poly-disperse aerosols with PSDs similar to those found in agricultural or urban conditions, respectively. Sampler testing was conducted in the Texas A&M wind tunnel using low volume samplers whose performance characteristics were evaluated. The samplers were

tested with three aerosols with different PSDs at three wind speeds (2-, 8-, and 24-km/hr) and five ambient aerosol concentrations ranging from 300- to 1,500-μg/m^3. The wind tunnel enabled reproducible test conditions as opposed to field testing of samplers.

"True PM_{10}" is considered to be that fraction of PM which includes all particles smaller than 10 μm in the air stream that is being sampled. True PM_{10} concentrations in the wind tunnel were determined using the PSD and mass concentration of aerosols sampled by an isokinetic probe. The mass fraction of PM smaller than 10 μm was multiplied by the PM concentration measured by the isokinetic sampler to determine the true PM_{10} concentration.

A TSP sampler can serve as a reference sampler in ambient sampling campaigns if the dust collected on the filter of the TSP sampler is representative of the ambient dust in terms of both PSD and mass concentration. When these conditions are fulfilled, a TSP sampler can be utilized with particle size analysis to measure true PM_{10} or $PM_{2.5}$ concentrations. This evaluation is important as isokinetic samplers can only be used when wind speed and direction are known and constant, which rarely occurs except under controlled testing conditions. The TSP samplers in the wind tunnel study were collocated with the isokinetic sampler. The TSP samplers in the wind tunnel tests were used to determine the validity of using low volume TSP samplers (Wanjura et al., 2005) as a field reference sampler for determining true PM_{10} concentrations. The results of this research lay the groundwork for understanding sampler performance in rural environments, making the equitable regulation of air pollution from agricultural industries possible.

CHAPTER III

THE EFFECT OF CHANGE IN SAMPLER FLOW RATE ON FRM PM_{10} SAMPLER PERFORMANCE

Introduction

The Federal Clean Air Act Amendments (CAAA) of 1970 created national goals and standards for air quality in the United States. The CAAA of 1970 required the Environmental Protection Agency (EPA) to enforce air pollution controls in the United States and required EPA to set National Ambient Air Quality Standards (NAAQS) for pollutants considered harmful to public health and welfare (USEPA, 1996). Established in 1971, the NAAQS are standards used to regulate six criteria air pollutants, including particulate matter (PM) (Federal Register, 1971). When the NAAQS were first established, PM was regulated on the basis of total suspended particulate (TSP). The 24-hr TSP standard of 260 $\mu g/m^3$ remained in place until 1987 when EPA replaced the TSP metric with PM_{10} and set the primary and secondary standards at 150 $\mu g/m^3$ (Federal Register, 1987). PM_{10} is that fraction of PM having an aerodynamic equivalent diameter (AED) less than or equal to 10 μm (CFR, 2006b). In 2006, EPA reviewed the NAAQS for PM and retained the 24-hr NAAQS for PM_{10} at 150 $\mu g/m^3$ (Federal Register, 2006).

PM concentrations in ambient air can be monitored by gravimetric sampling using Federal Reference Method (FRM) or other methods using Federal Equivalent Method (FEM) samplers. A sampler is designated as FRM or FEM under the provisions of 40 CFR, Part 53 (CFR, 2006b). EPA designates those PM_{10} samplers which meet the

requirements specified in 40 CFR, Part 53, Subpart D and meet additional specifications set forth in 40 CFR, Part 50, Appendix J (CFR, 2006c) as FRM samplers. Appendix J specifies a measurement principle based on extracting a sample from the atmosphere with a sampler that incorporates inertial separation of PM_{10} followed by collection of the PM_{10} on a filter over a 24-hr period. For a sampler to qualify as a FEM sampler, it 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 (CFR, 2006d).

Size selective PM samplers are employed to measure PM_{10} concentrations. Most size-selective PM samplers rely on a pre-collector inlet including an impactor plate that allows particles of a desired size to penetrate the sampler and collect on a filter while preventing undesired particles from penetrating the sampler and reaching the filter. These impactors work by rapidly changing the direction of air flow, which causes particles with more inertia to impact onto a plate (figure 4). The performance of a PM sampler is characterized by its fractional efficiency curve, which describes the collection efficiency of the sampler for a given size of particle.

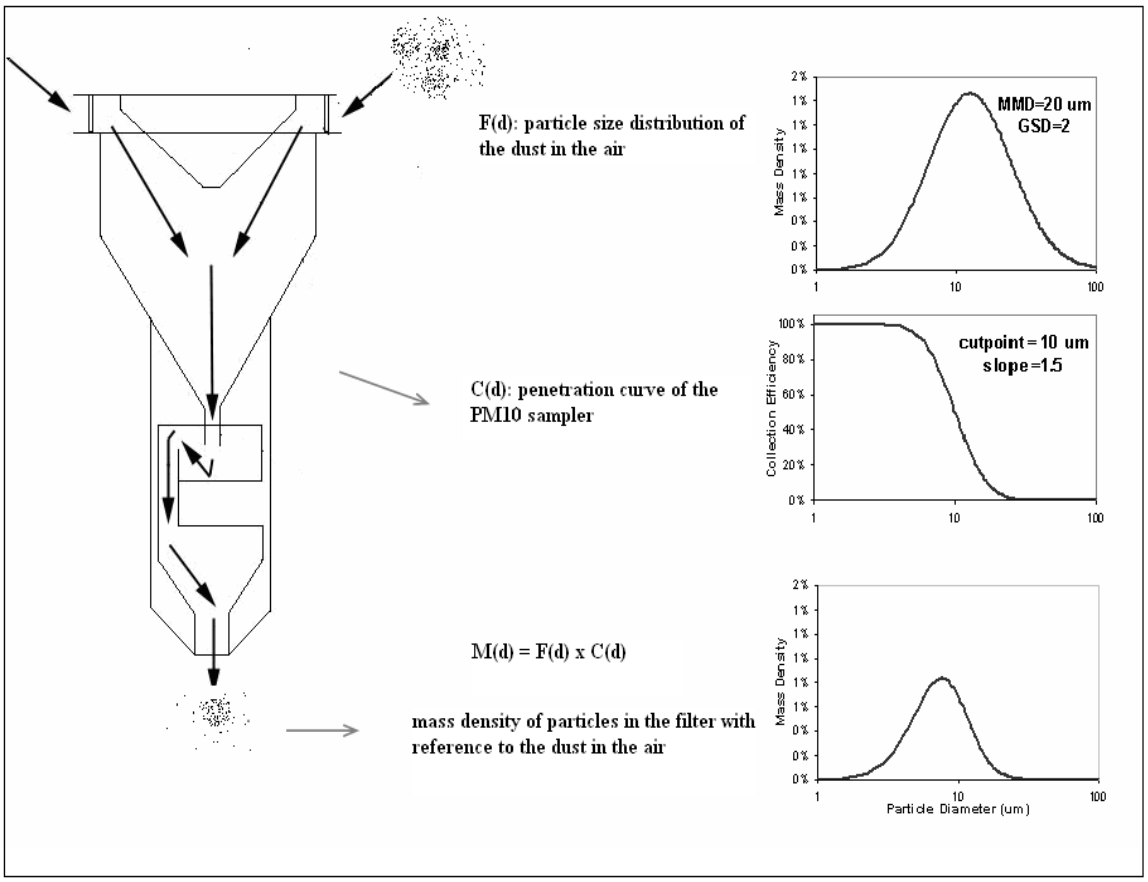

Figure 4. Illustration of interaction of particle size distribution and sampler performance characteristics of a typical PM_{10} inlet (Chen, 2007).

A PM_{10} pre-collector is designed to have performance characteristics that can be described by a cumulative lognormal probability distribution with a cutpoint (d_{50}) and a slope. The cutpoint of a sampler is defined as the particle diameter at which 50 percent of the particles of that size penetrate the pre-collector of the sampler and are deposited on the filter (Hinds, 1999). The slope of a sampler pre-collector's lognormal collection efficiency curve is defined as the ratio of the particle sizes corresponding to collection efficiencies of 84.1% and 50% ($d_{84.1}/d_{50}$) or 50% and 15.9% ($d_{50}/d_{15.9}$) or the square root of the ratio of $d_{84.1}/d_{15.9}$ (Hinds, 1999). An FRM PM_{10} sampler is required to have a

cutpoint of 10 ± 0.5 µm, and, although a slope value is not specifically stated in CFR (2001), idealized sampler performance curves in tabular form (CFR, 2001) allow for a slope of 1.5 ± 0.1 (Hinds, 1999). An example of the EPA FRM PM_{10} sampler's design efficiency curve is shown in figure 5.

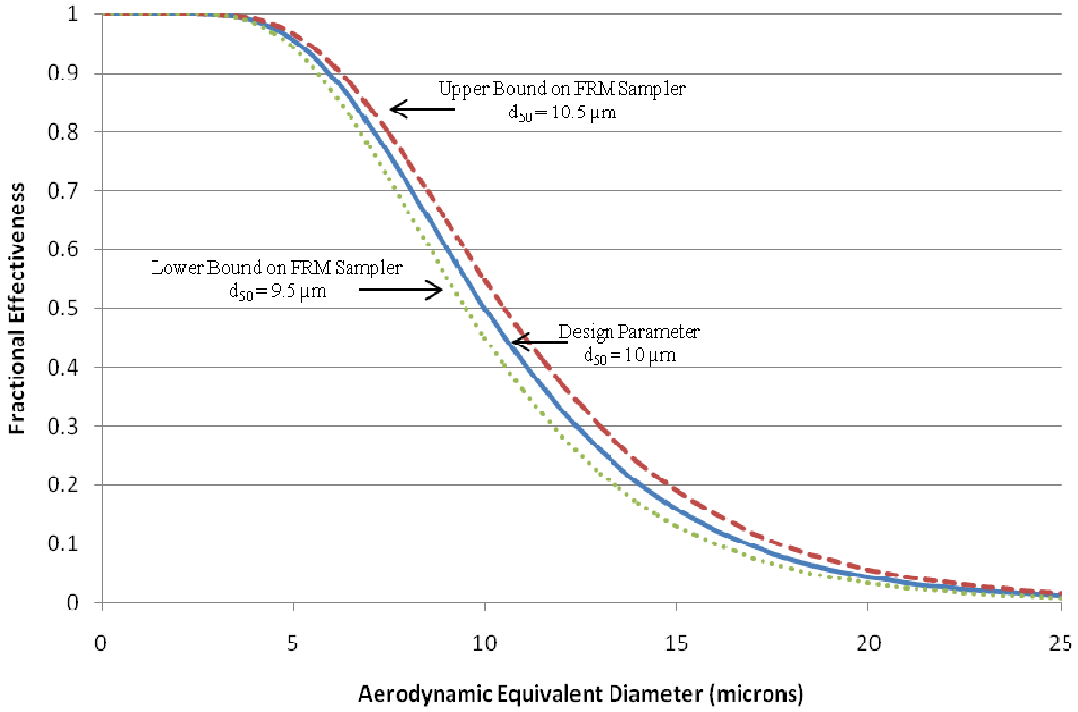

Figure 5. FRM guidelines for PM_{10} sampler efficiency curves (slopes are all equal to 1.5).

The expected mass density distribution of a sampled aerosol on the sampler filter can be determined using a PM sampler's fractional efficiency curve combined with the ambient particle size distribution (PSD) (Buser et al., 2007a). A PSD is a distribution of particles by volume, mass, or number. The mass distribution of ambient aerosol particles is the basis for regulation by EPA. Most ambient aerosols are represented by

PSDs that are lognormal in nature and characterized by a mass median diameter (MMD) and geometric standard deviation (GSD) (Hinds, 1999). The MMD is defined as the diameter for which half the mass of contributed by particles larger than the MMD, while the GSD is the standard deviation of the lognormal distribution.

If emitting sources of PM are to be regulated equitably, PM samplers must collect a representative (i.e. unbiased) sample of the ambient aerosol to which they are exposed in terms of concentration of the size fraction of interest (e.g. PM_{10}). To ensure that representative samples are collected, biases and errors associated with the use of FRM samplers must be well understood, including potential changes in sampler performance as meteorological conditions vary over the sampling period. Previous sampling campaigns by researchers at the Center for Agricultural Air Quality Engineering and Science (CAAQES) in the Texas Panhandle have shown diurnal temperature changes of up to 42°F that occur over an eight hour sampling period. Changes in air temperature impact air density, which will affect the volume flow rate of a sampler operating at a constant mass flow rate. This change in flow rate may cause samplers to operate under different conditions than those for which they were designed (i.e. 1 m^3/hr for low volume FRM PM_{10} samplers), possibly affecting the collection efficiency of the samplers. A 42°F temperature change would result in a 10 percent change in the sampler flow rate.

The objective of this research was to determine changes in the cutpoint of an FRM PM_{10} sampler at different sampler flow rates using the controlled conditions of a

wind tunnel with a poly-disperse dust at different wind speeds. This study explored if, and under what conditions, this FRM PM_{10} sampler performed as specified by the EPA.

Dust Wind Tunnel

Dust wind tunnels designed for aerosol studies, and particularly for PM sampler evaluation, are required by EPA to attain aerosol concentrations and wind speeds similar to those encountered in ambient environments (USEPA, 1987). The wind tunnel used in this study (henceforth "TAMU Wind Tunnel") was designed and fabricated by researchers at CAAQES at Texas A&M University. This wind tunnel conforms to EPA performance standards for uniformity of wind velocity and aerosol concentration specified in Title V of the CAAA of 1987 (USEPA, 1987) and 40 CFR Part 53, Subpart D (CFR, 2006b) (table 1). Appendix A describes the wind tunnel performance assessment tests that were performed on this wind tunnel.

Table 1. EPA requirements for the performance of wind tunnels for evaluating samplers (USEPA, 1987).

Parameter		PM_{10} Requirement
Air Velocity	*Uniformity*	±10% for 2, 8 and 24 km/h
	Measurement	1) Minimum of 12 test points 2) Monitoring techniques: precision ≤ 2% ; accuracy ≤ 5%
Aerosol Concentration	*Uniformity*	±10% of the mean
	Measurement	≥ 5 evenly spaced isokinetic samplers Sampling zone: horizontal dimension > 1.2 times the width of the test sampler at its inlet opening vertical dimension > 25 cm
Particle size	*Measurement*	Accuracy ≤ 0.15 μm; size resolution ≤ 0.1 μm

An overhead schematic of the wind tunnel is shown in figure 6. The centrifugal fan (1) (PLR206, New York Blower Co., Willowbrook, IL) is equipped with a variable frequency drive to regulate the speed of the fan. The wind tunnel body is located on an elevated platform to minimize vibration effects. The fan blows air through a vertical transmission duct which leads to a horizontal pre-mixing duct (2). The transition box (3) functions as an elbow to create turbulence while the dust generator (Wright Dust Feeder II, BGI Inc., Waltham, MA) is installed on top of the feeding duct (4). The feed point is oriented such that the dust enters the chamber against the direction of flow of air to enable more turbulent mixing. The inflow duct opens to the GTPS mixing chamber which contains a belt-drive, axial fan (Dayton 3C613, Dayton Co., Dayton, OH). The air exiting the GTPS chamber passes through the 1 m x 1 m flow-stabilizing duct (6). At the end of this duct is the test chamber (7), which has 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 passes through a 90º exhaust elbow (8) which directs the flow out through an exhaust fan on the roof (9).

The dust generator is equipped with a carbide blade to cut through the dust contained in a tightly packed cylindrical container. Prior to each test, dust was packed and the dust-packed container mounted on the feeder. (The dust packing procedures are located in Appendix B.) The dust generator has a variable range of output from 0.0026 to 60 g/hr of unit density dust.

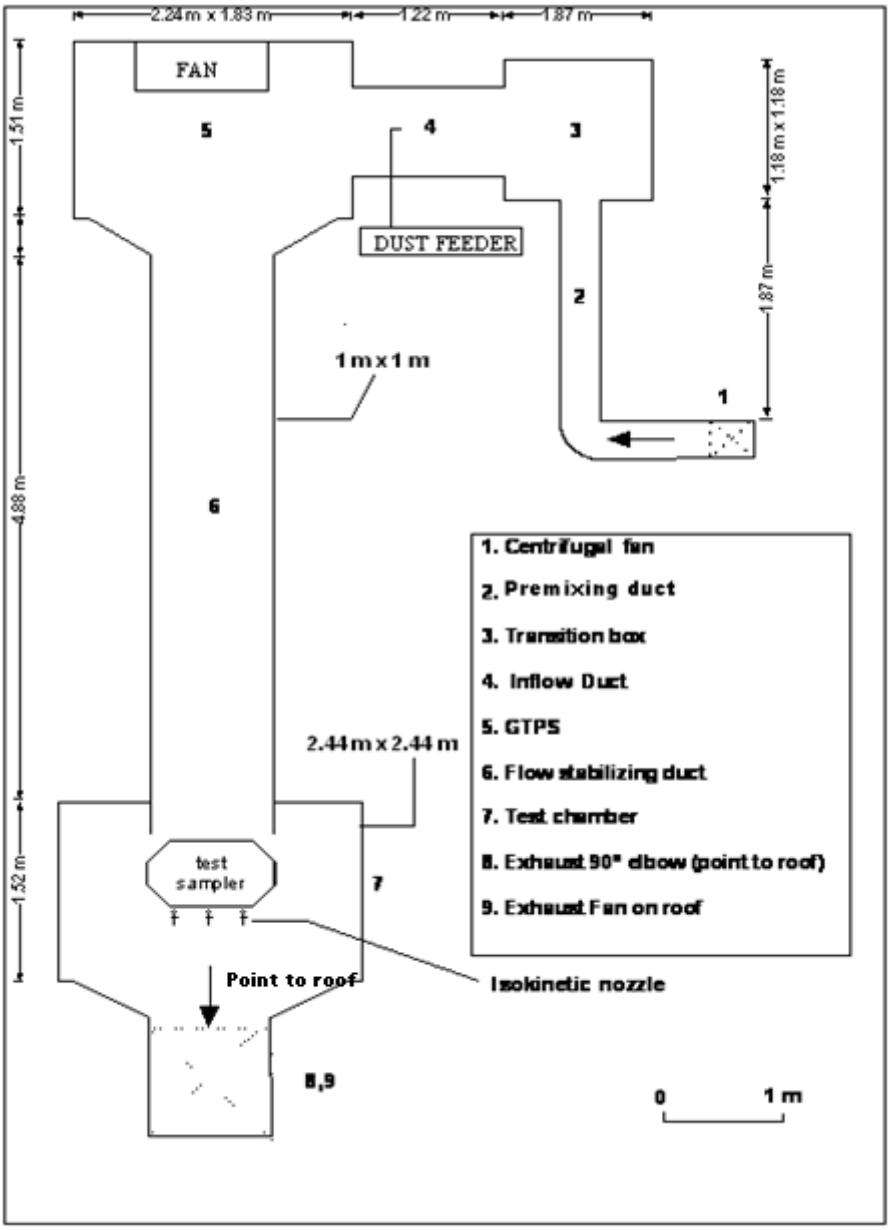

Figure 6. Schematic of the wind tunnel (Adapted from Chen, 2007).

Test Aerosol

PM sampling tests were carried out in the presence of a poly-disperse aerosol, as opposed to the mono-disperse aerosols used in previous EPA wind tunnel tests (Ranade

et al., 1990). Other previous wind tunnel studies (Dahmann et al., 2004; Witschger et al., 1997) used poly-disperse aerosols primarily because they more accurately represent aerosols encountered in the ambient environment. The dust selected for the wind tunnel tests was ultrafine Arizona road dust (ARD; A1 Ultrafine, Powder Technology Inc., Burnsville, MN)

The particle density of the ultrafine ARD was determined using a pycnometer (AccuPyc II 1330, Micromeritics, Norcross, GA). (The procedure for particle density analysis is located in Appendix D.) The ultrafine ARD had a particle density of 2.7 g/cm^3.

The shape factor of a particle relates the drag on an irregular particle to the drag on a spherical particle of the same volume (Hinds, 1999). A perfectly spherical particle has a shape factor of 1.0. The test dust for this study was imaged under an analytical-grade scanning electron microscope (SEM) (figure 7; JEOL-JSM 6400, JEOL USA Inc., Peabody, MA). The shape factor of the ultrafine ARD (angular particles) was assumed as 1.4 based on sharp and angular SEM images of ARD particles and literature on shape factor of quartz-type particles (Mark et al., 1985).

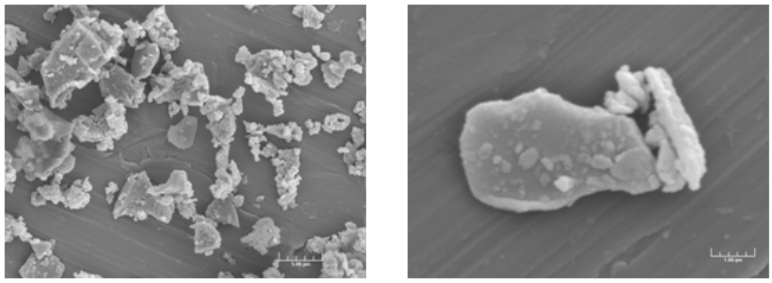

Figure 7. SEM images of ultrafine ARD.

Isokinetic Sampling System

An isokinetic sampling system was used to characterize the concentration and PSD of PM to which ambient samplers were exposed. Isokinetic inlet nozzle diameters of 19.8-, 10.2-, and 7.4-mm were used for sampling at three test wind speeds of 2-, 8-, and 24-km/hr, respectively, using a sampler flow rate of 1 m^3/hr (Chen, 2007). The isokinetic samplers utilized 47 mm polytetrafluoroethylene (PTFE) filters (Zefluor PTFE membrane, Pall Corp., East Hill, NY) and were connected to a stainless steel probe that was fitted into a rack. The rack allowed the isokinetic nozzle to be positioned at the entrance of the test chamber in the same vertical plane as the PM_{10} and TSP samplers. Air entering the isokinetic inlet was drawn through a pump (Thomas 927CA18, Gardner Denver Thomas, Sheboygan, WI) and a mass flow controller (MFC) (FMA5420-12VDC, Omega Inc., Stamford, CT). A LabVIEW program (LabVIEW 8.0, National Instruments, Austin, TX) was used to adjust flow through the MFC. The velocity in the sampler test chamber of the wind tunnel was measured using an air velocity transducer (TSI 8455, TSI Inc., Shoreview, MN) with a precision of 0.01 m/s and an accuracy of ± 0.5 percent of full scale of the selected range mounted on the outside of the wind tunnel.

The isokinetic sampler flow rate was determined using the measured wind velocity and air density calculations based on air temperature and relative humidity measurements from a thermal anemometer (Model 8386, TSI Inc., Shoreview, MN) and pressure measurements using a barometric pressure sensor (Model ASCX15AN, Honeywell, Inc., Morristown, NJ) located in the wind tunnel. Temperature, relative humidity, and barometric pressure measurements were taken every two seconds, and the air density was calculated by the LabVIEW program using equations 1 and 2. The sampling system was then adjusted accordingly to maintain a constant volumetric flow rate of 1 m^3/hr.

$$\rho_a = \frac{P_b - P_{wv}}{0.0028 \times (273 + t_{db})} + \frac{P_{wv}}{0.0046 \times (273 + t_{db})} \quad (1)$$

$$P_{wv} = \frac{RH}{100} \times P_s \quad (2)$$

where:

P_b = barometric pressure (atm),

P_{wv} = water vapor pressure (atm),

t_{db} = dry bulb temperature (°C),

RH = relative humidity (%), and

P_s = saturated water vapor pressure (atm).

The value of P_s was determined from the ASABE Psychrometric Data Standard (ASAE Standards, 2005) based on measurements of t_{db}.

Experimental Design

The performance of the BGI PM_{10} inlet (PQ/PM_{10}, BGI Inc., Waltham, MA) operating at three different sampler flow rates was evaluated. Experimental flow rates

were established by evaluating the potential change in flow rate of samplers deployed for an eight-hour test in the Texas Panhandle as temperature changes occurred. Air densities were determined using equations 1 and 2, assuming a constant relative humidity and barometric pressure of 0 percent and 1 atm, respectively. A maximum change in temperature of 42°F during an eight-hour period has been observed during previous field campaigns in the region.

Once the air densities for the starting and ending temperatures of 30°F and 72°F, respectively, were calculated, the change in flow rate of the samplers was calculated using equation 3.

$$Q_2 = Q_1 \times \frac{\rho_1}{\rho_2} \quad (3)$$

where:

Q_x = sampler flow rate at temperature x (m^3/hr) and

ρ_x = air density at temperature x (kg/m^3).

The results of this calculation showed that the sampler would realize a 10 percent change in volumetric flow rate over the duration of one eight hour sampling test period if the mass flow rate were kept constant. A 15 percent change in sampler flow rate for the tests performed was chosen to look at extreme cases of change in sampler flow rate. Therefore, tests were conducted at sampler flow rates of 0.85-, 1.0-, and 1.15-m^3/hr for this study.

Theoretical Analysis

The predicted values of the sampler cutpoint were calculated using the following equations derived from Stokes' law (Hinds, 1999). Equation 4 shows the first step in determining the cutpoint of the sampler. The diameter of the impactor jet for the BGI sampler was found to be 1.30 cm (0.512 in.) from 40 CFR Part 50, Appendix L (CFR, 2006e).

$$d_{50}\sqrt{C_c}=\left[\frac{9\pi\eta D_j^3(Stk_{50})}{4\rho_p Q}\right]^{1/2} \quad (4)$$

where:

$d_{50}\sqrt{C_c}$ = intermediate value (μm),

η = viscosity of the air (assumed as $1.81 * 10^{-5}$ Pa*s),

D_j = impactor jet diameter (μm),

Stk_{50} = Stokes number for 50 percent collection efficiency (0.24) (unitless),

ρ_p = particle density (μg/m^3), and

Q = sampler flow rate (m^3/hr).

The sampler cutpoint was then determined using eq. 5, an empirical equation developed because the Cunningham correction factor (C_c) is dependent on the cutpoint of the sampler (Hinds, 1999):

$$d_{50}=d_{50}\sqrt{C_c}-0.078 \quad (5)$$

where:

d_{50} = cutpoint of the sampler (μm).

It is important to note that the cutpoint of the sampler is not dependent on the wind speed to which the sampler is exposed.

Empirical Analysis

Three PM_{10} sampler inlets were used to concurrently test the three different sampler flow rates and were placed in the same vertical test plane as the isokinetic sampler inlet in the test chamber (figure 8). The samplers were arranged in the test chamber so that less than 15 percent of the cross section was obstructed as specified by EPA (CFR, 2006b). Ultrafine ARD was fed into the wind tunnel by the dust generator to achieve a target concentration of 750 $\mu g/m^3$.

A randomized complete block design with replication as the blocking factor was used. Three replications of each treatment were performed. Tests were conducted over three wind speeds of 2-, 8- , and 24-km/hr. A test duration of two hours was established to ensure that the minimum mass of dust required on a filter to ensure a successful PSD analysis (1 mg) was achieved.

The filters used for collecting the sampled dust were 47 mm polytetrafluoroethylene (PTFE) filters (Zefluor PTFE membrane, Pall Corp., East Hill, NY). The filters were weighed on a precision analytical balance (AG 245, Mettler - Toledo Inc., Columbus, OH). For quality control purposes, 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 filter weighing protocol is located in Appendix C.)

Figure 8. Photograph of the test chamber with the isokinetic and PM_{10} sampler inlets.

Particulate Matter Sampling System

The sampler flow rate control boxes were designed at Texas A&M University and were placed outside the wind tunnel. Sampler inlets were connected to a calibrated sharp edge orifice meter using 0.95 cm (3/8 in.) inner diameter tubing. Figure 9 illustrates the set up of the low volume PM_{10} sampling system.

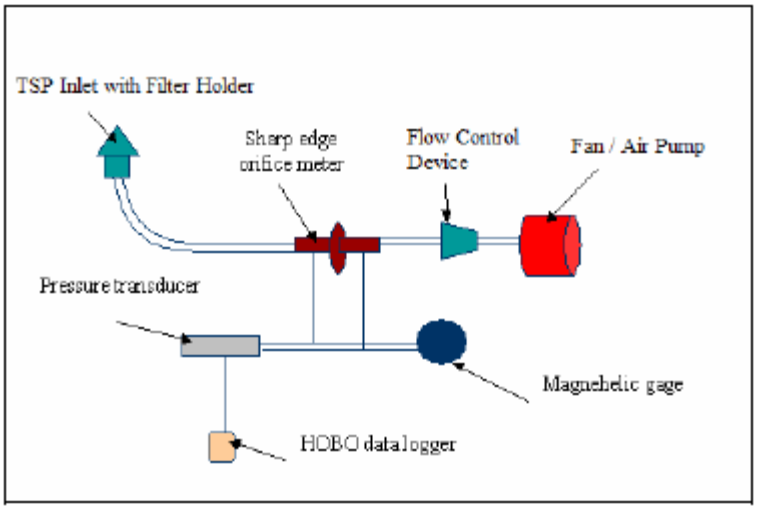

Figure 9. Low volume PM_{10} sampler set up (Wanjura, 2005).

A 0.09 kW (1/8 hp) diaphragm pump (Thomas 927CA18, Gardner Denver Thomas, Sheboygan, WI) provided air flow, which was adjusted using a ball valve. The airflow rate was monitored by measuring the pressure differential across a calibrated sharp-edge orifice with a differential pressure transducer (PX274, Omega Engineering, Inc., Stamford, CT). The pressure differential was recorded every two seconds using a data logger (HOBO U12-006, Onset Computer Corp, Pocasset, MA).

The flow rate of sampled air was calculated using equation 6:

$$Q=3.478\times K\times D_o^2\times\sqrt{\frac{\Delta P}{\rho_a}} \qquad (6)$$

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 the sharp-edged orifice meter (mm H_2O), and

ρ_a = air density (kg/m^3).

The volumetric flow rates of the low volume samplers were set at 0.85-, 1.0, and 1.15-m^3/hr, respectively, at the beginning of each test. The valve controlling sampler flow rate was not adjusted during any test. For quality control, the pressure drop across the sharp-edged orifice meter was recorded manually at the beginning and end of each test. (Procedures for calibrating the differential pressure transducers are located in Appendix E.) The data recorded by the HOBO data loggers was used to calculate the actual sampler flow rates.

Wind Tunnel Testing Protocol

Pre-experimental Preparation

Depending upon the wind speed at which a test was conducted, the isokinetic inlet with the corresponding nozzle diameter was fit into a probe in the center of the chamber cross-section. The full-scale range of the velocity transducer was set before each test depending on the wind speed. Four clean, numbered, pre-weighed filters were placed in the sampler cassettes of the three test samplers and the isokinetic inlet. Log sheets were maintained to record the filter numbers used in each of the four inlets.

Wind Tunnel Testing

The centrifugal and exhaust fans were turned on, and the speed of the centrifugal fan was adjusted to achieve the desired wind speed. Wind speed in the test section was measured using an anemometer (Model 8386, TSI Inc., Shoreview, MN). When the

desired wind speed was achieved, the dust generator was turned on. The feed rate of the dust generator was determined using data given by the manufacturer depending on the bulk density of the dust, ambient aerosol concentration desired, and wind speed. The pressure of the compressed air supply was maintained between 8- and 15- psig, based on manufacturer recommendations. All four sampler pumps were then turned on and the flow rates adjusted until the desired pressure drop across each sharp-edge orifice (as determined from the orifice meter calibration) was achieved. (A detailed explanation of the calibration of the sharp-edge orifice meters is in Appendix F.) The data loggers were launched at the start of each test to log the current output of the pressure transducer (4-20 mA). The test start and end times were noted in log sheets. During each test, the dust generator was monitored to ensure proper operation. At the end of each test, the sampler pumps were turned off and the data loggers stopped. The dust generator and compressed air supply were then turned off, followed by the centrifugal and exhaust fans. (Detailed operating procedures for this wind tunnel are located in Appendix G.)

Post-experimental Protocol

Filters were removed from the sampler inlets, placed in petri-dishes and taken to a controlled environment to condition for a minimum of 24 hr before post-weighing. The volume of air sampled during a given test was determined by integrating the flow rates as determined by the pressure differentials across the sharp-edged orifice meters over the duration of the test.

Concentration and PSD Analysis

The mass of PM deposited on each filter determined by subtracting the filter pre-weight from the post-weight was divided by the total volume flow of air passed over the filter in each test to determine the concentration of PM collected by each sampler (eq. 7 and 8).

$$C=\frac{M}{V} \quad (7)$$

$$V=Q\times t \quad (8)$$

where:

C = measured PM concentration ($\mu g/m^3$),

M = mass of PM deposited on the filter during a given test (μg),

V = total volume of air sampled (m^3),

Q = volume flow rate (m^3/hr), and

t = test duration, (hr).

A particle size analysis of the PM from each filter was performed using a Malvern Mastersizer with a Hydro SM attachment (Mastersizer 2000, Malvern Instruments Ltd., Westborough, MA). (The particle sizing protocol is described in Appendix H.) The analysis yielded the volume fractions of particles ranging from 0.25 to 55 μm over 100 logarithmically-sized bins. The generated PSDs were converted from equivalent spherical diameter (ESD) to AED using equation 9.

$$AED=ESD\times\sqrt{\frac{\rho}{\rho_w\times\chi}} \quad (9)$$

where:

ρ = particle density (g/cm^3),

χ = particle shape factor (dimensionless), and

ρ_w = density of water = 1 (g/cm^3).

Data Analysis

The lognormal mass density distribution (f) of most ambient dusts can be expressed according to equation 10.

$$f(d_p, MMD, GSD) = \frac{1}{d_p \ln(GSD)\sqrt{2\pi}} \exp\left[\frac{-(\ln d_p - \ln MMD)^2}{2(\ln GSD)^2}\right] \quad (10)$$

where:

d_p = particle diameter (μm).

Because the dust collected on the isokinetic sampler filter is expected to be representative of the aerosol challenging each sampler in the wind tunnel, the PSD of the isokinetic filters was treated as the PSD of the dust to which the samplers were exposed, hereafter referred to as the ambient PSD (f_{amb}). The dust collected on the filter of a size-selective PM_x sampler is known as "measured PM" and the PSD represented by f_{samp}.

Sampler performance was documented by characterizing the cutpoint and slope of a sampler's fractional efficiency curve (FEC), which describes the efficiency of a size selective sampler to remove particles from the air stream drawn into the sampler and prevent them from penetrating to the filter. Equation 11 expresses the lognormal collection efficiency density function of a PM pre-separator.

$$FEC(a,d_{50}, slope)=\int_{0}^{d_p} \frac{1}{a \ln(slope) \sqrt{2\pi}} \exp\left[\frac{-(\ln a - \ln d_{50})^2}{2(\ln(slope))^2}\right] dd_p \quad (11)$$

where:

FEC(a,d_{50},slope) = fractional efficiency curve of the PM sampler for particles having diameters less than *a* and

a = diameter of particle at which collection efficiency is being calculated (μm).

d_{50} = cutpoint of sampler (μm), and

slope = slope of sampler (dimensionless).

The efficiency of a size selective sampler to allow penetration of the pre-separator by particles of a given size and collect them on a filter is described by the sampler penetration curve (Buser et al., 2008). The penetration efficiency is defined as:

$$P_x(a, d_{50}, slope)=1-FEC(a, d_{50}, slope) \quad (12)$$

where:

P_x(a,d_{50}, slope) = penetration efficiency of a PM_x pre-separator for a particle with diameter *d_p*.

The expected PM_x concentrations of each particle size range on a sampler filter can be determined by combining equations 10 and 12 into equation 13.

$$C_{samp}=C_{amb}\int_{a}^{b} \left(f_{amb}(d_p, MMD, GSD)\times P_x(d_p, d_{50}, slope)\right) dd_p \quad (13)$$

where:

C_{samp} = expected mass concentration on a PM_x sampler filter ($\mu g/m^3$),

C_{amb} = ambient PM concentration collected on isokinetic filter ($\mu g/m^3$),

a = lower size limit of particle size range of interest (μm),

b = upper size limit of particle size range of interest (μm), and

d_p = particle diameter (μm)

The difference between the measured and expected concentrations of PM_x within each particle size bin (i) is represented by a quantity J.

$$J=\sum_{i=0}^{100}\left(f_{amb}\left(d_{p,i},MMD,GSD\right)\left(1\text{-}FEC_{samp}\left(d_{p,\,i},d_{50},slope\right)\text{-}f_{samp}\left(d_{p,\,i},MMD,GSD\right)\right)\right) \quad (14)$$

To determine the remaining unknown parameters (i.e. cutpoint and slope of the samplers), the value of "J" (eq. 14) was minimized using the Solver function in Microsoft Excel (Microsoft Office Excel 2007, Microsoft, Redmond, WA). This process of solving equation 14 for the sampler performance characteristics is referred to as the "sampler performance characteristic estimation process". The constraints applied during minimization of "J" were: cutpoint (upper limit = 50 µm, lower limit = 1 µm) and slope (upper limit = 5, lower limit = 1). This methodology was used to determine the "best fit" cutpoints and slopes for the samplers used in this study.

The only factor in these tests was wind speed, with levels of 2-, 8-, and 24-km/hr, with three replications for a total of nine runs. The response variables for this analysis

were the measured cutpoint and concentration of the PM_{10} samplers, the PSD of the dust collected by the isokinetic sampler, and the true PM_{10} concentration.

After removing outlying data points that were more than three standard deviations away from the mean, the normality of the data was examined using the Box-Cox test in Design-Expert (Design-Expert 7.1.6, Stat-Ease, Inc., Minneapolis, MN). Analysis of variance (ANOVA) tests were conducted using the linear model function in Design-Expert with an error level of $\alpha = 0.05$ and a null hypothesis that the difference between the means of the cutpoints and the FRM cutpoint value of 10 μm equaled zero for the sampler flow rates used in this study. Means were compared using least significant difference (LSD) tests in Design-Expert. ANOVA tests ($\alpha = 0.05$) comparing the difference in the true PM_{10} concentration from the isokinetic sampler and the concentration from the PM_{10} samplers as determined by equations 7 and 8 were performed with a null hypothesis that the difference was equal to zero.

Results and Discussion

Theoretical Cutpoint Analysis

Predicted cutpoints of the BGI sampler as volume flow rates varied are shown in table 2. Based on theoretical analysis, the sampler operating in the presence of ultrafine ARD would have a cutpoint outside the guidelines specified by EPA for a flow rate of 1.15 m^3/hr. The theoretical cutpoint values in table 2 show that the performance of the FRM PM_{10} sampler is not robust under conditions in which the sampler is operated

above the design flow rate. This result points to the need for precise and dynamic flow control over the duration of a given test.

Table 2. Preliminary cutpoint calculations for different sampler flow rates.

Dust	Flow Rate (m^3/hr)	Cutpoint (µm)
Ultrafine ARD	0.85	10.31
Ultrafine ARD	1.0	9.50
Ultrafine ARD	1.15	8.85

Empirical Cutpoint Data Analysis

After testing for normality of the data using the Box-Cox method in Design-Expert, the PM_{10} cutpoint data was transformed using the natural log function before any further analysis was completed.

Significant differences in the difference between the measured cutpoint and the FRM value of 10 µm were detected as a function of wind speed ($p = 0.0043$). Figure 10 shows the trend in the difference in the cutpoint values and the FRM value of 10 µm with relation to the test wind speed. The vertical lines on each point in figure 10 show the least significant difference interval and the red horizontal lines indicate the minimum and maximum FRM values of 9.5- and 10.5-µm, respectively.

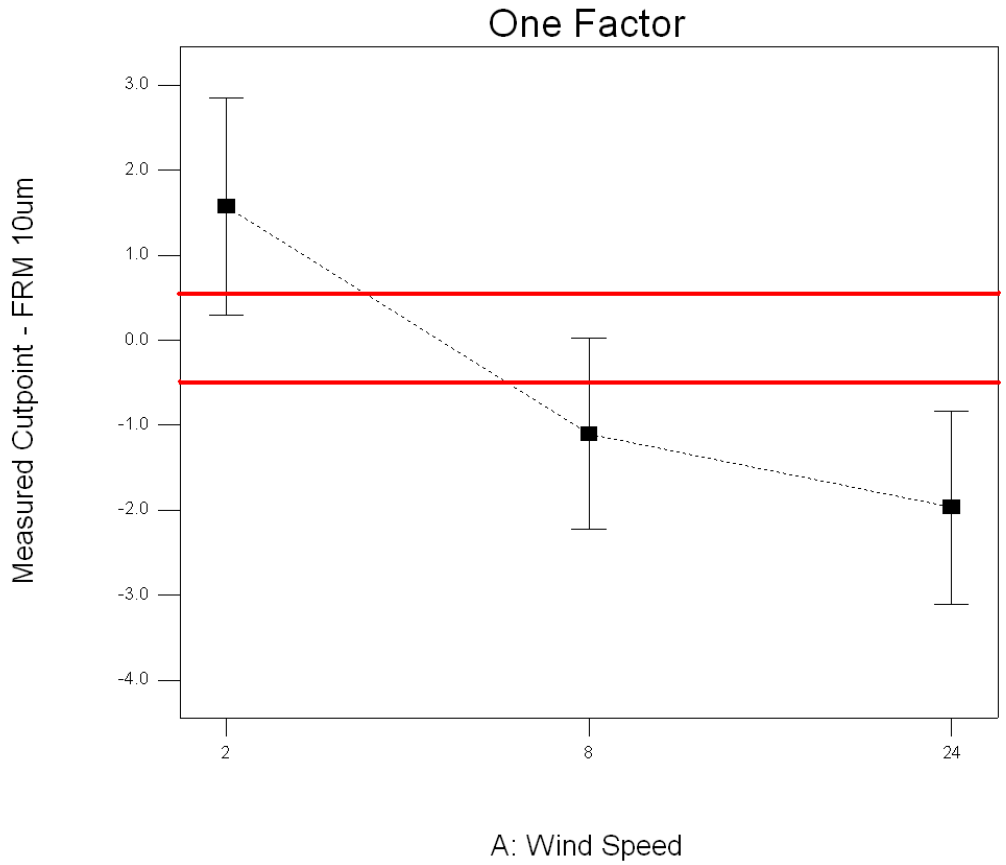

Figure 10. The difference between measured cutpoint values for the PM_{10} sampler and the FRM value of 10 µm based on test wind speed. The red horizontal lines indicate the minimum and maximum FRM values of 9.5- and 10.5-µm, respectively.

The difference in the measured cutpoint values and the FRM value of 10 µm in figure 10 demonstrate that as the test wind speed increased, the difference in the measured cutpoint value from the PM_{10} sampler and the FRM value of 10 µm decreased. The average cutpoint value measured by the PM_{10} samplers in these tests was 8.77 ± 1.3 µm. This interaction is not fully understood and will need to be investigated further through more in-depth wind tunnel testing. These results are not explained by the theoretical calculation of the cutpoint presented in equations 4 and 5, but the wind speed

may have an effect on the Stk_{50} value that is dependent on the sampler operating as designed and is dependent on the ambient air velocity. These results affirm the conclusion from Ono et al. (2000) that the cutpoint of samplers may decrease with increasing wind speed.

Measured Concentration Analysis

The results from the ANOVA test ($\alpha = 0.05$) conducted comparing the difference between the measured PM_{10} sampler concentrations and the true PM_{10} concentrations show that there were no significant factors ($p = 0.2439$). The mean difference between the measured and true PM_{10} concentrations for these tests was 71.8 ± 40.9 $\mu g/m^3$, which means that the PM_{10} samplers were over-sampling the amount of PM_{10} that was present in the ambient air. Based on theoretical sampler performance evaluation (Buser et al., 2007b), it is expected that the FRM PM_{10} samplers would under-sample when in the presence of ultrafine ARD, so these results are not as expected from previous theoretical research.

Conclusions

For sources of PM to be regulated equitably, the biases and errors associated with the use of FRM PM_{10} samplers must be accounted for and accurately characterized. The results of this study show that the diurnal change in temperature that may occur during normal sampling of ambient PM can affect the sampler flow rate so that measured cutpoint values are outside of EPA FRM guidelines for the cutpoint of PM_{10} samplers

(10 ± 0.5 μm). The test wind speed had an effect on the cutpoint of the samplers; as the test wind speed increased, the difference between the measured sampler cutpoint and the FRM value of 10 μm decreased. The concentrations measured by the FRM PM_{10} samplers over-sampled the amount of PM_{10} present during testing when compared to the true PM_{10} concentrations as measured by the isokinetic sampler. The sampler flow rate was not found to be significant to the measured cutpoint or the measured concentration. This means that the ambient temperature changes do not significantly affect the performance of the FRM PM_{10} sampler tested for this research.

CHAPTER IV

WIND TUNNEL EVALUATION OF FRM PM_{10} AND LOW VOLUME TSP SAMPLERS

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 Amendments (CAAA) 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 regulate PM_{10}, which is that fraction of PM having an aerodynamic equivalent diameter (AED) less than or equal to 10 μm (Federal Register, 1987). This change from regulating TSP to PM_{10} reflected the purpose of the NAAQS to protect public health as PM_{10} is more representative of the particle size that poses a health threat (Federal Register, 1987). EPA currently uses PM_{10} as an indicator of the concentration of particles with an aerodynamic equivalent diameter (AED) less than or equal to 10 μm but greater than 2.5 μm, known as inhalable coarse particles (PM_c or PM_{coarse}). In 2006, the primary 24-hour PM_{10} standard of 150 $\mu g/m^3$ (99^{th} percentile) was reaffirmed in order to gather more data about measured PM_c concentrations, which may lead to promulgation of a concentration

standard for PM_c in the future. EPA, however, revoked the annual PM_{10} standard as available health evidence did not suggest a substantial link between long-term exposure to PM_{10} and health concerns (CFR, 2006b). The secondary PM_{10} standards are equivalent to the primary standards.

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. Faulkner et al. (2007) and Buser et al. (2007a) documented systematic biases associated with the use of federal reference method (FRM) size-selective PM samplers, particularly the over-sampling biases seen when sampling PM characterized by particles larger than the cutpoint 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 adverse sampling conditions, including sampling of larger particles and operation under heavy PM loading, are encountered when sampling PM downwind of agricultural operations and could potentially affect the equity of regulation between industries.

Measurement of PM_{10} is performed using 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, 2006c). FRM size-selective samplers have a pre-separator inlet that is intended to allow particles of a desired size to be captured on a filter and 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 cutpoint (d_{50}) and a slope. The cutpoint of a sampler is the particle diameter at which 50 percent of the PM penetrates the pre-separator and is deposited on the filter, and 50 percent is captured by the pre-separator (Hinds, 1999). EPA specifies a cutpoint of 10 ± 0.5 μm for PM_{10} samplers (CFR, 2006b).

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). Although the EPA does not specify the sampler slope in 40 CFR, Part 53, they present idealized sampler performance curves in tabular form (CFR, 2001) from which the sampler performance slope can be calculated as 1.5 ± 0.1 for PM_{10} samplers (Hinds, 1999).

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., 2007a). 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 FRM PM_{10} sampler's design efficiency curve is shown in figure 5.

"True PM_{10}" is considered to be that fraction of PM which includes all particles smaller than 10 μm in the air stream that is being sampled. True PM_{10} concentrations in

ambient sampling campaigns can be determined using the PSD and mass concentration of aerosols sampled by a low volume TSP sampler if the dust collected on the filter of the TSP sampler is representative of the ambient dust in terms of both PSD and mass concentration. The mass fraction of PM smaller than 10 μm is multiplied by the PM concentration measured by the TSP sampler to determine the true PM_{10} concentration. This technique of using TSP samplers to determine true PM_{10} is utilized in the studies described by Buser et al. (2008), Goodrich et al. (2009), and Wang et al. (2005a). An evaluation of sampler performance of low volume TSP samplers is important as isokinetic samplers can only be used when wind speed and direction are known and constant, which rarely occurs except under controlled testing conditions.

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 research was to evaluate the performance of FRM PM_{10} and low volume TSP samplers under the controlled conditions of a wind tunnel. The specific objectives of this research were as follows:

1. Empirically investigate changes in the performance of two FRM PM_{10} samplers operating in the presence of poly-disperse PM with changes in particle size distribution (PSD), aerosol concentration, and wind speed.
2. Empirically determine if the concentrations and PSDs from testing of low volume TSP samplers can be used for determining true PM_{10} concentrations by performing collocated testing of TSP and isokinetic samplers in the wind tunnel.

Methods

Dust Wind Tunnel

Dust wind tunnels designed for PM sampler evaluation are required by EPA to attain aerosol concentrations and wind speeds similar to those encountered in ambient environments (USEPA, 1987). The wind tunnel used in this study (henceforth "TAMU Wind Tunnel") was designed and fabricated by researchers at Texas A&M University. This wind tunnel conforms to EPA performance standards for uniformity of wind velocity and aerosol concentration specified in Title V of the CAAA of 1987 (USEPA, 1987) and 40 CFR Part 53, Subpart D (CFR, 2006b) (table 3).

Table 3. EPA requirements for the performance of wind tunnels for evaluating samplers (USEPA, 1987).

Parameter		PM_{10} Requirement
Air Velocity	*Uniformity*	±10% for 2, 8 and 24 km/h
	Measurement	1) Minimum of 12 test points 2) Monitoring techniques: precision ≤ 2% ; accuracy ≤ 5%
Aerosol Concentration	*Uniformity*	±10% of the mean
	Measurement	≥ 5 evenly spaced isokinetic samplers Sampling zone: horizontal dimension > 1.2 times the width of the test sampler at its inlet opening vertical dimension > 25 cm
Particle size	*Measurement*	Accuracy ≤ 0.15 μm; size resolution ≤ 0.1 μm

An overhead view of the wind tunnel is shown in figure 6. The centrifugal fan (1) (PLR206, New York Blower Company, Willowbrook, IL) is equipped with a variable frequency drive to regulate the speed of the fan. The wind tunnel body is

located on an elevated platform to minimize vibration effects. The fan blows air through a vertical transmission duct which leads to a horizontal pre-mixing duct (2). The transition box (3) functions as an elbow to create turbulence while the dust feeder (Wright Dust Feeder II, BGI Inc., Waltham, MA) is installed on top of the feeding duct (4). The feed point is oriented such that dust enters the chamber against the direction of air flow to enable more turbulent mixing. The inflow duct opens to the GTPS mixing chamber (5) which contains a belt-drive, axial fan (Dayton 3C613, Dayton, Co., Dayton, OH). The air exiting the GTPS chamber passes through the 1 m x 1 m flow-stabilizing duct (6). At the end of this duct is the test chamber (7), which has an expanded cross sectional area to avoid wall effects and to permit testing of multiple PM samplers simultaneously. Air coming out of the test chamber passes through a 90º exhaust elbow (8) which directs the flow out through an exhaust fan on the roof (9).

The dust generator is equipped with a carbide blade to cut through the dust contained in a tightly packed cylindrical container. Prior to each test, the dust was packed and the dust-packed container mounted on the feeder. (Dust packing procedures are located in Appendix B.) The dust generator has a variable range of output from 0.0026 to 60 g/hr of unit density dust.

Isokinetic Sampling System

An isokinetic sampling system was used to characterize the concentration and PSD of PM to which ambient samplers were exposed. Isokinetic inlet nozzle diameters of 19.8-, 10.2-, and 7.4-mm were used for sampling at three test wind speeds of 2-, 8-,

and 24-km/hr, respectively, using a sampler flow rate of 1 m^3/hr (Chen, 2007). The isokinetic samplers utilized 47 mm polytetrafluoroethylene (PTFE) filters (Zefluor PTFE membrane, Pall Corp., East Hill, NY) and were connected to a stainless steel probe that was fitted into a rack. The rack allowed the isokinetic nozzle to be positioned at the entrance of the test chamber in the same vertical plane as the PM_{10} and TSP samplers. Air entering the isokinetic inlet was drawn through a pump (Thomas 927CA18, Gardner Denver Thomas, Sheboygan, WI) and a mass flow controller (MFC) (FMA5420-12VDC, Omega Inc., Stamford, CT). A LabVIEW program (LabVIEW 8.0, National Instruments, Austin, TX) was used to adjust flow through the MFC. The velocity in the sampler test chamber of the wind tunnel was measured using an air velocity transducer (TSI 8455, TSI Inc., Shoreview, MN) with a precision of 0.01 m/s and an accuracy of ± 0.5 percent of full scale of the selected range mounted on the outside of the wind tunnel.

The isokinetic sampler flow rate was determined using the measured wind velocity and air density calculations based on air temperature and relative humidity measurements from a thermal anemometer (Model 8386, TSI Inc., Shoreview, MN) and pressure measurements using a barometric pressure sensor (Model ASCX15AN, Honeywell, Inc., Morristown, NJ) located in the wind tunnel. Temperature, relative humidity, and barometric pressure measurements were taken every two seconds, and the air density was calculated by the LabVIEW program using equations 15 and 16. The volumetric flow rate of the isokinetic sampling system was then adjusted accordingly to maintain a volumetric flow rate of 1 m^3/hr.

$$\rho_a = \frac{P_b - P_{wv}}{0.0028 \times (273 + t_{db})} + \frac{P_{wv}}{0.0046 \times (273 + t_{db})} \quad (15)$$

$$P_{wv} = \frac{RH}{100} \times P_s \quad (16)$$

where:

P_b = barometric pressure (atm),

P_{wv} = water vapor pressure (atm),

t_{db} = dry bulb temperature (°C),

RH = relative humidity (%), and

P_s = saturated water vapor pressure (atm).

The value of P_s was determined from the ASABE Psychrometric Data Standard (ASAE Standards, 2005) based on measurements of t_{db}.

Test Aerosols

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). Some previous wind tunnel studies (Dahmann et al., 2004; Witschger et al., 1997) used poly-disperse aerosols primarily because they more accurately represent aerosols encountered in the ambient environment. Typical urban PM has a mass median diameter (MMD) around 5.7 μm (USEPA, 1996) while agricultural dusts have MMDs ranging from 15 to 25 μm (Faulkner et al., 2007). Three dusts were selected for use in this study based on their varying MMD and geometric standard deviations (GSD) values (table 4).

Table 4. Dusts used for sampler evaluation.

Dust	MMD (μm AED)	GSD
Ultrafine ARD[a, b,]	5.27	1.63
Fine ARD[a, c]	12.05	1.72
Cornstarch	17.14	1.51

[a] ARD = Arizona Road Dust
[b] A1 Ultrafine, Powder Technology Inc., Burnsville, MN
[c] A2 Fine, Powder Technology Inc., Burnsville, MN

The particle densities of all aerosols were determined using a pycnometer (AccuPyc II 1330, Micromeritics, Norcross, GA). The aerosols had particle densities of 2.7 g/cm^3 (ultrafine ARD and fine ARD) and 1.5 g/cm^3 (cornstarch).

The shape factor of a particle relates the drag on an irregular particle to the drag on a spherical particle of the same volume (Hinds, 1999). A perfectly spherical particle has a shape factor of 1.0. The test dusts for this study were imaged under an analytical-grade scanning electron microscope (SEM) (figure 11; JEOL-JSM 6400, JEOL USA Inc., Peabody, MA). Based on the near-spherical images of cornstarch particles, Wang et al. (2005b) assumed the shape factor of cornstarch as 1.0. Because the SEM images of cornstarch particles are not perfectly spherical, the shape factor of cornstarch was assumed to be 1.05 for this study. The shape factor of ARD (angular particles) was assumed as 1.4 based on sharp and angular SEM images of ARD particles and literature on shape factor of quartz-type particles (Mark et al., 1985).

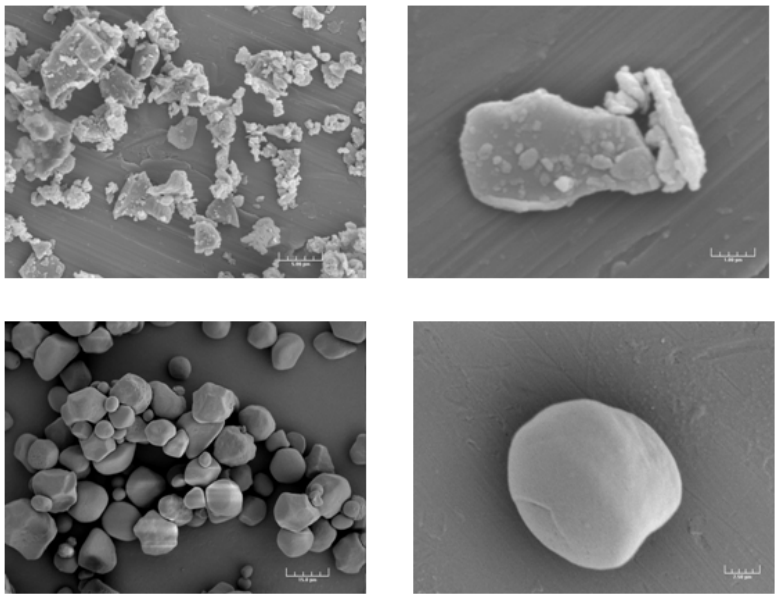

Figure 11. SEM images of ARD (top left, top right) and cornstarch (bottom left, bottom right).

Experimental Design

The performance of a Graseby Andersen PM_{10} inlet (henceforth, the flat-head PM_{10} inlet) (SA246B, Thermo Andersen, Smyrna, GA) and a BGI PM_{10} inlet (henceforth, the louvered-head PM_{10} inlet) (PQ/PM_{10}, BGI Inc., Waltham, MA), were evaluated. Collocated in the same vertical plane in the test chamber with the two PM_{10} samplers and the isokinetic sampler were two low volume TSP samplers: a dome-top TSP inlet and a cone-top TSP inlet (figure 12). The samplers were arranged in the test chamber so that less than 15 percent of the cross section was obstructed as specified by EPA (CFR, 2006b). The systems used to establish and control the flow rate of the PM_{10} and TSP samplers were identical and are described in detail by Buser et al. (2008).

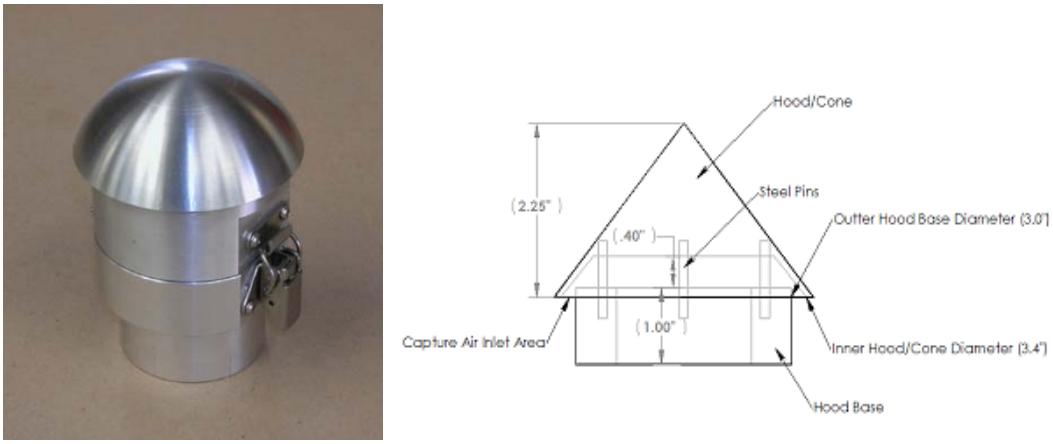

Figure 12. Dome-top TSP inlet (left) and side view of the low volume cone-top TSP inlet (units are in inches) (Wanjura et al., 2005) (right).

The filters used for collecting the sampled dust were weighed on a precision analytical balance (AG 245, Mettler - Toledo Inc., Columbus, OH) before and after use in the wind tunnel. For quality control purposes, 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 filter weighing protocol is located in Appendix C.)

A 0.09 kW (1/8 hp) diaphragm pump (Thomas 927CA18, Gardner Denver Thomas, Sheboygan, WI) provided air flow, which was adjusted using a ball valve. The airflow rate was monitored by measuring the pressure differential across a calibrated sharp-edge orifice with a differential pressure transducer (PX274, Omega Engineering, Inc., Stamford, CT). The pressure differential was recorded every two seconds using a data logger (HOBO U12-006, Onset Computer Corp, Pocasset, MA).

The flow rate of sampled air was calculated using equation 17:

$$Q=3.478\times K\times D_o^2\times\sqrt{\frac{\Delta P}{\rho_a}} \qquad (17)$$

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 the sharp-edged orifice meter (mm H_2O), and

ρ_a = air density (kg/m^3).

The volumetric flow rate of the low volume samplers was set at 1.0 m^3/hr at the beginning of each test. The valve controlling sampler flow rate was not adjusted during any test. The pressure drop across the sharp-edged orifice meter was manually recorded at the beginning and end of each test. (Procedures for calibrating the differential pressure transducers are located in Appendix E.)

A three factorial randomized complete block design with replication as the blocking factor was used. Three replications of each treatment were performed. Tests were conducted over three wind speeds of 2-, 8-, and 24-km/hr; target ambient aerosol concentrations of 300-, 500-, 950-, 1250-, and 1500-μg/m^3; and with the three aerosols listed in table 6. Test durations from one to eight hours were established based on aerosol PSD and ambient aerosol concentration so that the minimum mass of dust required on a filter to ensure a successful PSD analysis (0.6 mg) was achieved.

Concentration and PSD Analysis

The mass of PM deposited on each filter determined by subtracting the filter pre-weight from the post-weight value was divided by the total volume of air passed through

the filter in each test to determine the concentration of PM collected by each sampler (eq. 18 and 19).

$$C=\frac{M}{V} \quad (18)$$

$$V=Q\times t \quad (19)$$

where:

C = measured PM concentration ($\mu g/m^3$),

M = mass of PM deposited on the filter during a given test (μg),

V = total volume of air sampled (m^3),

Q = volume flow rate (m^3/hr), and

t = test duration, (hr).

A particle size analysis of the PM from each filter was performed using a Malvern Mastersizer with a Hydro SM attachment (Mastersizer 2000, Malvern Instruments Ltd., Westborough, MA). (The particle sizing protocol is described in Appendix H.) The analysis yielded the volume fractions of particles ranging from 0.25 to 55 μm over 100 logarithmically-sized bins. The generated PSDs were converted from equivalent spherical diameter (ESD) to AED using equation 20.

$$AED=ESD\times\sqrt{\frac{\rho}{\rho_w\times\chi}} \quad (20)$$

where:

ρ = particle density (g/cm^3),

χ = particle shape factor (dimensionless), and

ρ_w = density of water = 1 (g/cm^3).

Data Analysis

The lognormal mass density distribution (f) of most ambient dusts can be expressed according to equation 21.

$$f(d_p, MMD, GSD) = \frac{1}{d_p \ln(GSD)\sqrt{2\pi}} \exp\left[\frac{-(\ln d_p - \ln MMD)^2}{2(\ln GSD)^2}\right] \quad (21)$$

where:

d_p = particle diameter (μm).

Because the dust collected on the isokinetic sampler filter is expected to be representative of the aerosol challenging each sampler in the wind tunnel, the PSD of the isokinetic filters was treated as the PSD of the dust to which the samplers were exposed, hereafter referred to as the ambient PSD (f_{amb}). The dust collected on the filter of a size-selective PM_x sampler is known as "measured PM" and the PSD represented by f_{samp}.

Sampler performance was documented by characterizing the cutpoint and slope of a sampler's fractional efficiency curve (FEC), which describes the efficiency of a size selective sampler to remove particles from the air stream drawn into the sampler and prevent them from penetrating to the filter. Equation 22 expresses the lognormal collection efficiency density function of a PM pre-separator.

$$FEC(a, d_{50}, slope) = \int_0^{d_p} \frac{1}{a \ln(slope)\sqrt{2\pi}} \exp\left[\frac{-(\ln a - \ln d_{50})^2}{2(\ln(slope))^2}\right] dd_p \quad (22)$$

where:

FEC(a,d_{50},slope) = fractional efficiency of the PM sampler for particles of diameter *a*,

d_{50} = cutpoint of sampler (μm), and

slope = slope of sampler (dimensionless).

The efficiency of a size selective sampler to allow penetration of the pre-separator by particles of a given size and collect them on a filter is described by the sampler penetration curve (Buser et al., 2008). The penetration efficiency is defined as:

$$P_x(a, d_{50}, \text{slope}) = 1 - FEC(a, d_{50}, \text{slope}) \quad (23)$$

where:

$P_x(a,d_{50}, slope)$ = penetration efficiency of a PM_x pre-separator for a particle with diameter *a*.

The expected PM_x concentrations of each particle size range on a sampler filter can be determined by combining equations 21 and 23 into equation 24.

$$C_{samp} = C_{amb} \int_a^b \left(f_{amb}(d_p, MMD, GSD) \times P_x(d_p, d_{50}, \text{slope}) \right) dd_p \quad (24)$$

where:

C_{samp} = expected mass concentration on a PM_x sampler filter (μg/m^3),

C_{amb} = ambient PM concentration collected on isokinetic filter (μg/m^3),

a = lower size limit of particle size range of interest (μm),

b = upper size limit of particle size range of interest (μm), and

d_p = particle diameter (μm)

The difference between the measured and expected concentrations of PM_x within each particle size bin (i) is represented by a quantity J.

$$J=\sum_{i=0}^{100}\left(f_{amb}\left(d_{p,i},MMD,GSD\right)\left(1\text{-}FEC_{samp}\left(d_{p,\,i},d_{50},slope\right)\text{-}f_{samp}\left(d_{p,\,i},MMD,GSD\right)\right)\right) \quad (25)$$

To determine the remaining unknown parameters (i.e. cutpoint and slope of the samplers), the value of "J" (eq. 25) was minimized using the Solver function in Microsoft Excel (Microsoft Office Excel 2007, Microsoft, Redmond, WA). This process of solving equation 25 for the sampler performance characteristics is referred to as the "sampler performance characteristic estimation process". The constraints applied during minimization of "J" were: cutpoint (upper limit = 50 μm, lower limit = 1 μm) and slope (upper limit = 5, lower limit = 1). This methodology was used to determine the "best fit" cutpoints and slopes for the samplers used in this study.

The factors in these tests were wind speed, with levels of 2-, 8-, and 24-km/hr, dust type, with levels of ultrafine ARD, fine ARD, and cornstarch, and ambient aerosol concentration, with levels of 300-, 500-, 950-, 1250-, and 1500-μg/m^3 with three replications for a total of 129 runs. (Due to limitations from the dust feeder used, cornstarch could not be tested at 1250- or 1500-μg/m^3 at the test wind speeds of 8- or 24-km/hr.) The response variables for this analysis were the measured cutpoint and slope of the PM_{10} samplers and the measured cutpoint, slope, and concentration of the TSP samplers.

After removing outlying data points that were more than three standard deviations away from the mean, the normality of the data was examined using the Box-Cox test in Design-Expert (Design-Expert 7.1.6, Stat-Ease, Inc., Minneapolis, MN). Analysis of variance (ANOVA) tests were conducted using the linear model function in Design-Expert with an error level of $\alpha = 0.05$ and a null hypothesis that the difference between the means of the cutpoints or slopes and the FRM cutpoint value of 10 μm or FRM slope value of 1.5, respectively, equaled zero. Means were compared using least significant difference (LSD) tests in Design-Expert. ANOVA tests ($\alpha = 0.05$) comparing the differences in the concentrations measured by the TSP samplers as determined by equations 18 and 19 and the concentrations from the isokinetic samplers were performed with a null hypothesis that the difference was equal to zero.

Results and Discussion

PM_{10} Cutpoint and Slope

After testing for normality of the data using the Box-Cox method in Design-Expert, the flat and louvered PM_{10} cutpoint data was transformed using the natural log function and the flat and louvered PM_{10} slope data was transformed using the square root function before any further analysis was completed.

Significant differences in the difference between the measured cutpoint and the FRM value of 10 μm were detected as a function of dust type for the flat PM_{10} sampler ($p = 0.0096$). Figure 13 shows the trend in the difference between the measured cutpoint and the FRM value of 10 μm. The vertical lines on each data point show the least

significant difference interval for each dust type and the horizontal red lines show the FRM minimum and maximum limits of 9.5- and 10.5-µm, respectively.

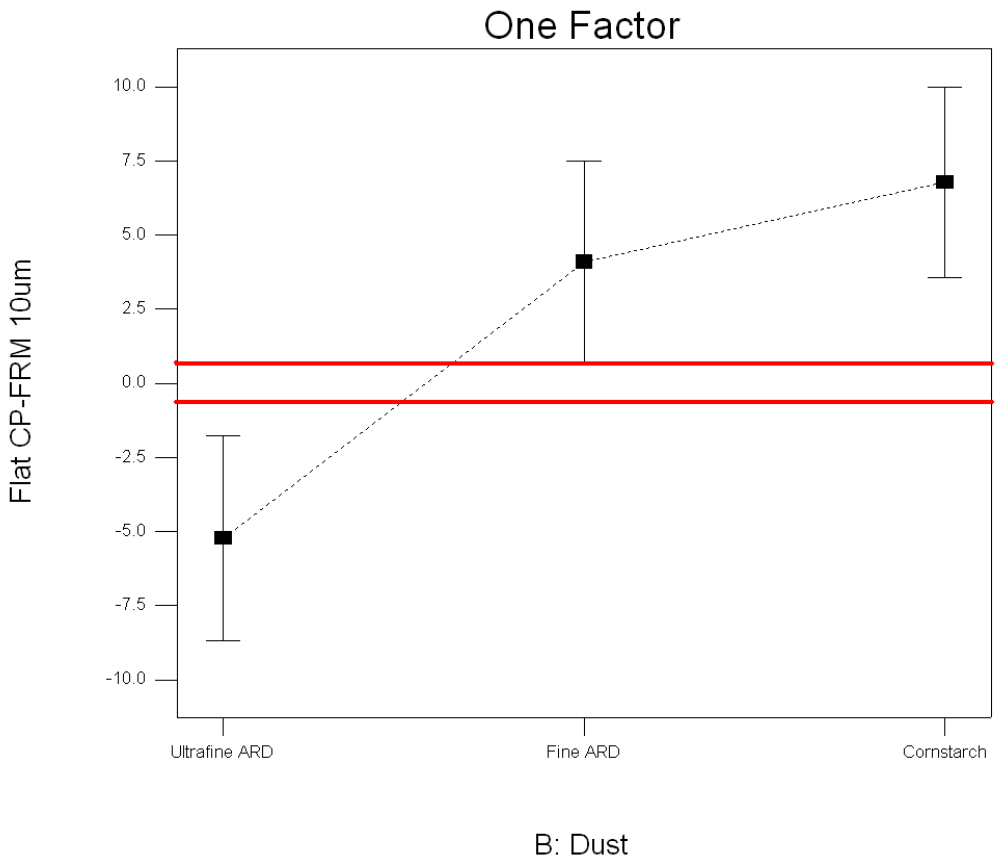

Figure 13. The difference between measured cutpoint values for the flat PM_{10} sampler and the FRM value of 10 µm based on dust type. The red horizontal lines indicate the minimum and maximum FRM values of 9.5- and 10.5-µm, respectively.

Differences in the difference between the measured slope of the flat PM_{10} sampler and the FRM value of 1.5 were detected as a function of dust type ($p = 0.0240$). Figure 14 shows the trend in the difference between the measured slope and the FRM value of 1.5. The vertical lines show the least significant difference interval for each

dust type and the horizontal red line indicates the maximum FRM value of 1.6. As the MMD of the dust increased, the difference between the measured slope and the FRM slope value of 1.5 increased.

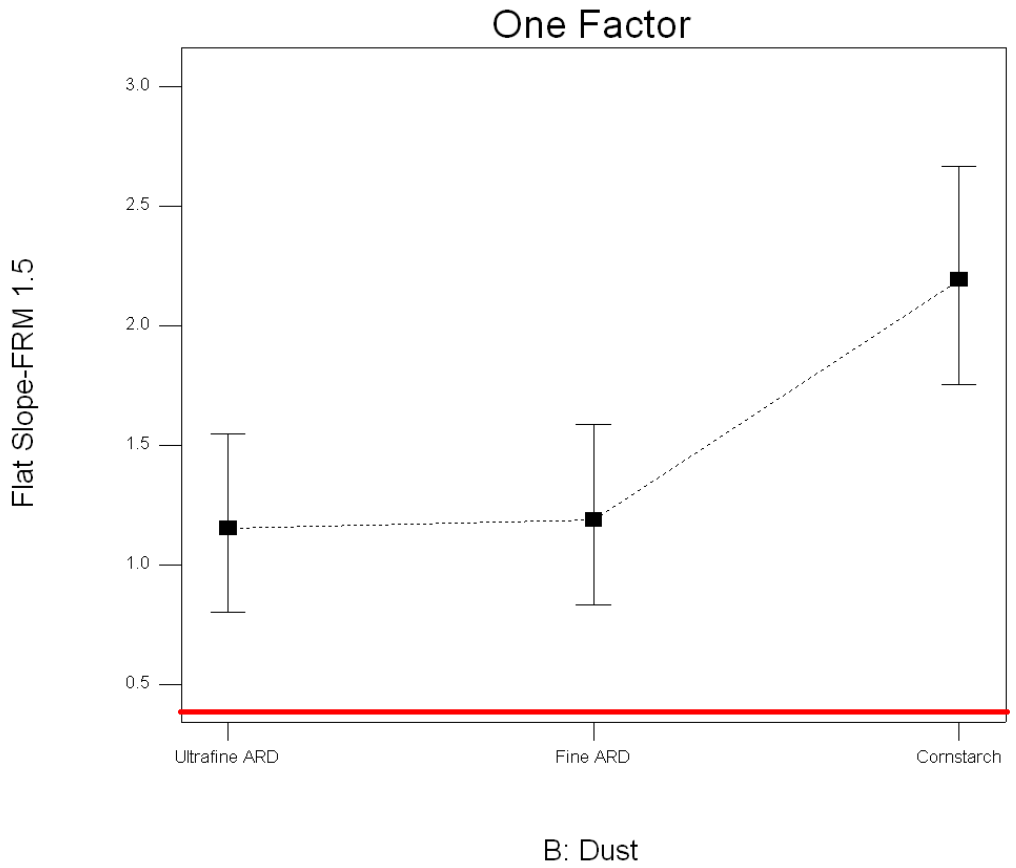

Figure 14. The difference between measured slope values for the flat PM_{10} sampler and the FRM value of 1.5 based on dust type. The horizontal red line indicates the maximum FRM value of 1.6.

Statistical differences were detected in the measured cutpoint of the louvered PM_{10} sampler as a function of dust type ($p = 0.0017$). Figure 15 shows the trend in the difference between the measured cutpoint and the FRM value of 10 µm. The vertical

lines show the least significant difference interval for each dust type and the horizontal red lines indicate the minimum and maximum FRM values of 9.5- and 10.5-µm, respectively. As the MMD of the dust increased, the difference between the measured cutpoint and the FRM value of 10 µm increased.

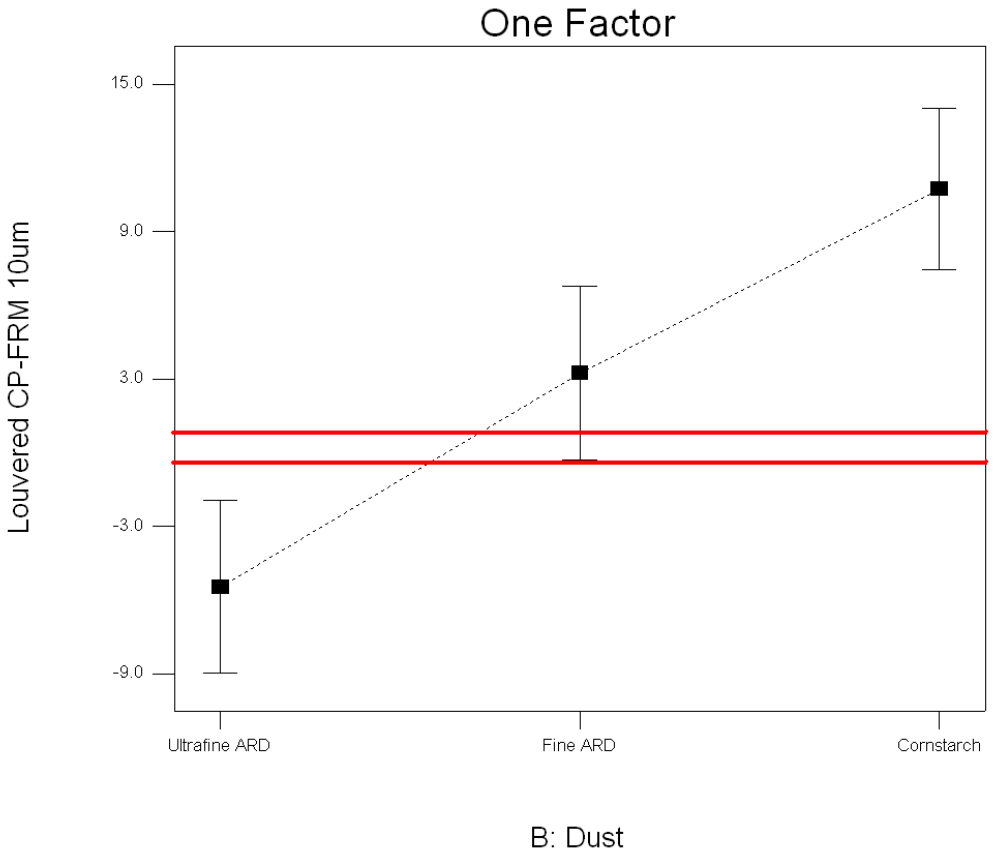

Figure 15. The difference between measured cutpoint values for the louvered PM_{10} sampler and the FRM value of 10 µm based on dust type. The horizontal red lines indicate the minimum and maximum FRM values of 9.5- and 10.5-µm, respectively.

There were no significant factors detected in the measured slope of the louvered PM_{10} sampler. The mean value of the measured slope of the louvered PM_{10} sampler was 3.49 ± 0.28. This value is higher than the FRM upper limit of 1.6.

There were no significant interactions between the factors for the cutpoint or slope of the flat or louvered PM_{10} samplers.

For the ultrafine ARD, both the flat and louvered PM_{10} samplers had a cutpoint that was lower than the minimum FRM value of 9.5 μm. The cutpoint values measured by both the flat and louvered PM_{10} samplers in the presence of either fine ARD or cornstarch were significantly higher than the maximum FRM value of 10.5 μm. This shift in cutpoint with relation to the MMD of the sampled dust is similar to what was described previously by Buser et al. (2007a) and Faulkner et al. (2007).

TSP Cutpoint and Slope

After testing for normality of the data using the Box-Cox method in Design-Expert, the cone and dome TSP cutpoint data were transformed using the square root and natural log function, respectively before any further analysis was completed.

Because the measured MMD and GSD of the cone and dome TSP were statistically different ($p < 0.009$) from the measured MMD and GSD from the isokinetic sampler (table 5), the cutpoint and slope of both these TSP samplers were analyzed. This statistical difference means that the TSP samplers do not collect PSDs that are representative of the ambient aerosol.

Table 5. MMD and GSD values for the isokinetic, cone TSP, and dome TSP samplers.

Sampler	Mean Cutpoint[a, b]	Mean Slope[a, b]
Isokinetic	12.33 ± 1.0 a	1.68 ± 0.05 c
Cone TSP	10.68 ± 0.6 b	2.25 ± 0.07 d
Dome TSP	11.01 ± 0.2 b	2.27 ± 0.09 d

[a] Means are shown with a 95 percent confidence interval.
[b] No differences were detected ($\alpha = 0.05$) in values in the same column followed by the same letter.

There were no significant factors detected in the measured cutpoint of the cone TSP sampler. The mean value of the measured cutpoint of the cone TSP sampler was 20.40 ± 3.06 μm.

Significant differences in the measured slope were detected as a function of dust type for the cone TSP sampler ($p = 0.0092$). The mean values of the measured slope of the cone TSP sampler separated by dust type are shown in table 6.

Table 6. Slope values from the cone TSP sampler separated by dust type.

Dust	Mean Slope[a, b]
Ultrafine ARD	2.79 ± 0.52 a
Fine ARD	3.24 ± 0.55 a, b
Cornstarch	3.80 ± 0.44 b

[a] Means are shown with a 95 percent confidence interval.
[b] No differences were detected ($\alpha = 0.05$) in values in the same column followed by the same letter.

Measured slope values from the cone TSP sampler based on dust MMD are shown in figure 16. This figure demonstrates that as the MMD of the dust sampled increased, the measured slope of the cone TSP sampler increased. The error bars show the least significant difference interval for each data point.

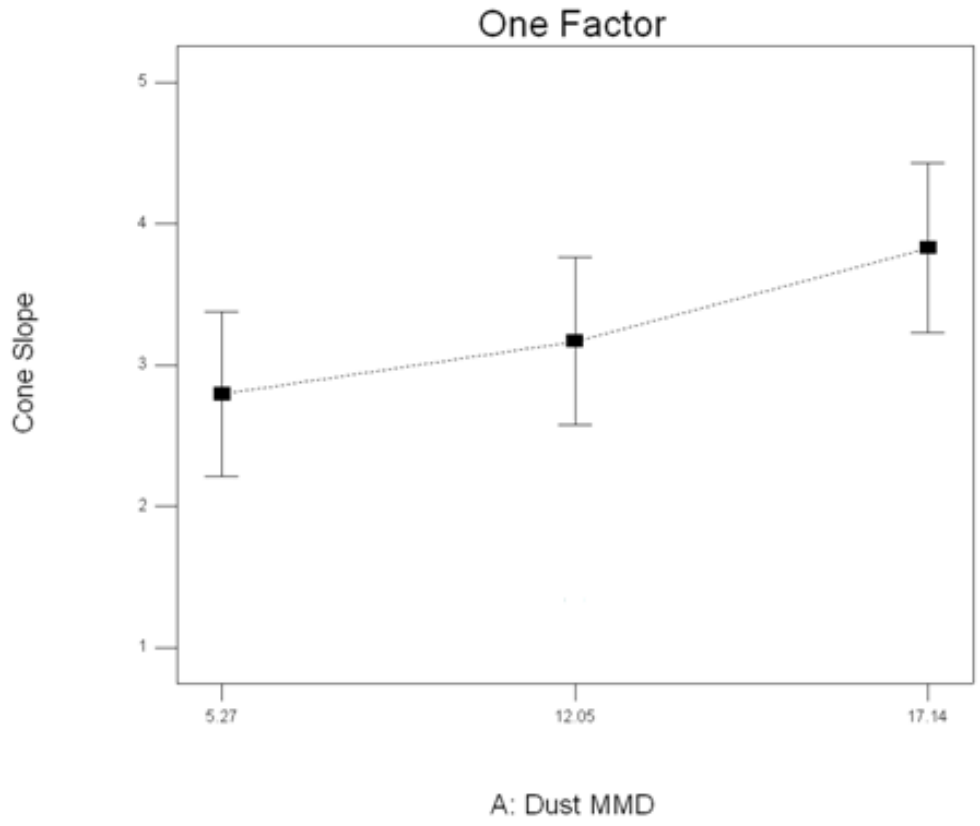

Figure 16. Slope values from the cone TSP inlet based on dust MMD.

There were no significant factors detected in the measured cutpoint of the dome TSP sampler. The mean value of the measured cutpoint of the dome TSP sampler was 19.74 ± 1.64 μm.

Statistical differences were detected in the measured slope of the dome TSP sampler as a function of dust type ($p = 0.0013$). The mean values for the measured slope of the dome TSP sampler based on dust type are shown in table 7.

Table 7. Slope values from the dome TSP sampler separated by dust type.

Dust	Mean Slope[a, b]
Ultrafine ARD	2.86 ± 0.50 a
Fine ARD	3.11 ± 0.55 a
Cornstarch	4.49 ± 0.30 b

[a] Means are shown with a 95 percent confidence interval.
[b] No differences were detected ($\alpha = 0.05$) in values in the same column followed by the same letter.

A significant interaction ($p = 0.0422$) between ambient aerosol concentration and test wind speed was detected for the slope values of the dome TSP inlet. Measured slope values from the dome TSP sampler based on ambient aerosol concentration and test wind speed are shown in figure 17. This graph shows that as the concentration of the ambient aerosol and the test wind speed increased, the slope of the dome TSP sampler decreased.

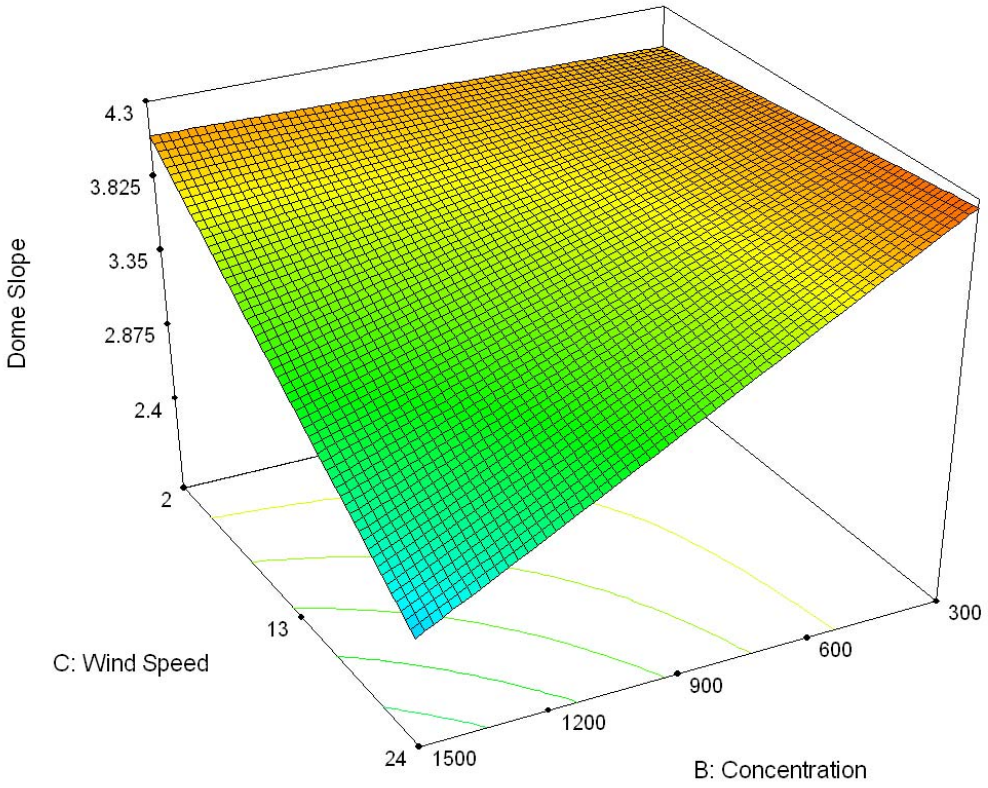

Figure 17. Slope values from the dome TSP inlet based on aerosol concentration and test wind speed.

TSP Concentration

Statistical differences in the difference between the measured concentration from the cone TSP inlets and the concentration measured from the isokinetic inlet were detected as a function of ambient aerosol concentration ($p = 0.0065$). Figure 18 shows the trend in the difference between the concentration measured by the cone TSP sampler and the concentration measured by the isokinetic inlet based on the ambient aerosol concentration. The vertical bars show the least significant difference interval for each ambient aerosol concentration and the horizontal red line is where the difference between the cone TSP concentration and the isokinetic concentration is zero. As the ambient aerosol concentration increased, the difference between the concentration measured by the cone TSP sampler and the concentration measured by the isokinetic inlet increased.

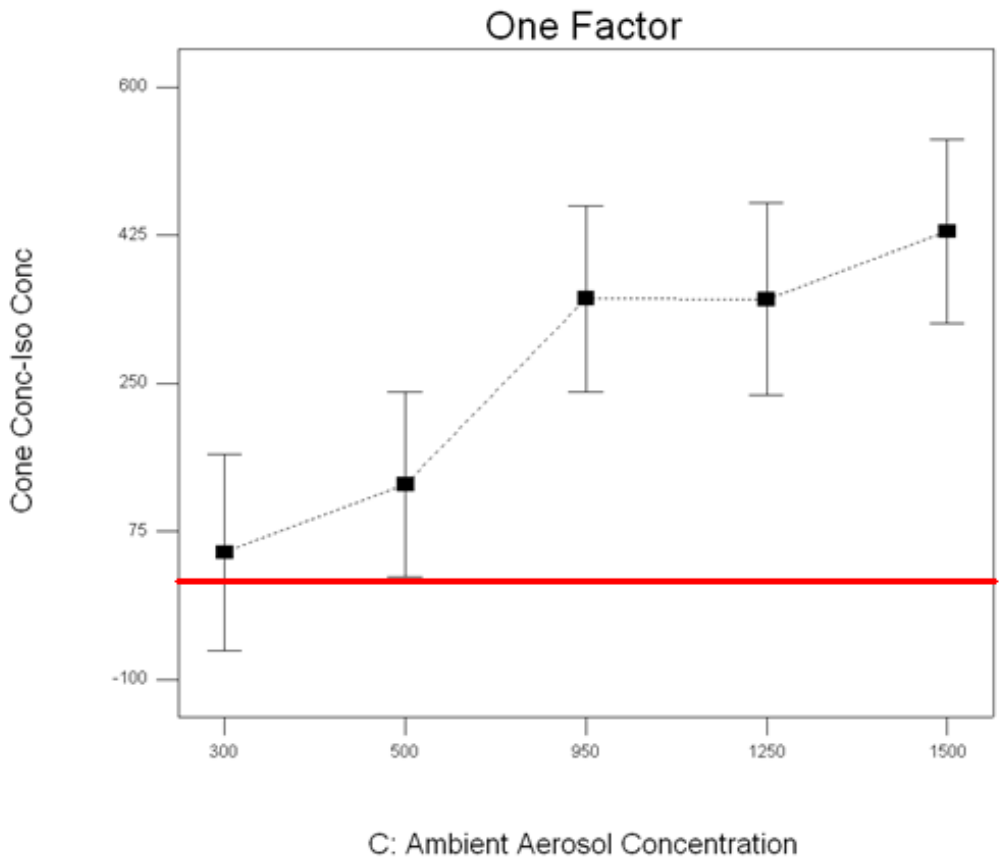

Figure 18. The difference between the concentration measured by the cone TSP sampler and the concentration measured by the isokinetic inlet based on ambient aerosol concentration. The horizontal red line is where the difference between the cone TSP concentration and the isokinetic concentration is zero.

Statistical differences in the difference between the measured concentration from the dome TSP inlets and the measured concentration from the isokinetic inlets were detected as a function of ambient aerosol concentration ($p = 0.0173$). Figure 19 shows the trend in the difference between the concentration measured by the dome TSP sampler and the concentration measured by the isokinetic inlet based on the ambient aerosol concentration. The vertical bars show the least significant difference interval for each ambient aerosol concentration. As the ambient aerosol concentration increased, the

difference between the concentration measured by the dome TSP sampler and the concentration measured by the isokinetic inlet increased.

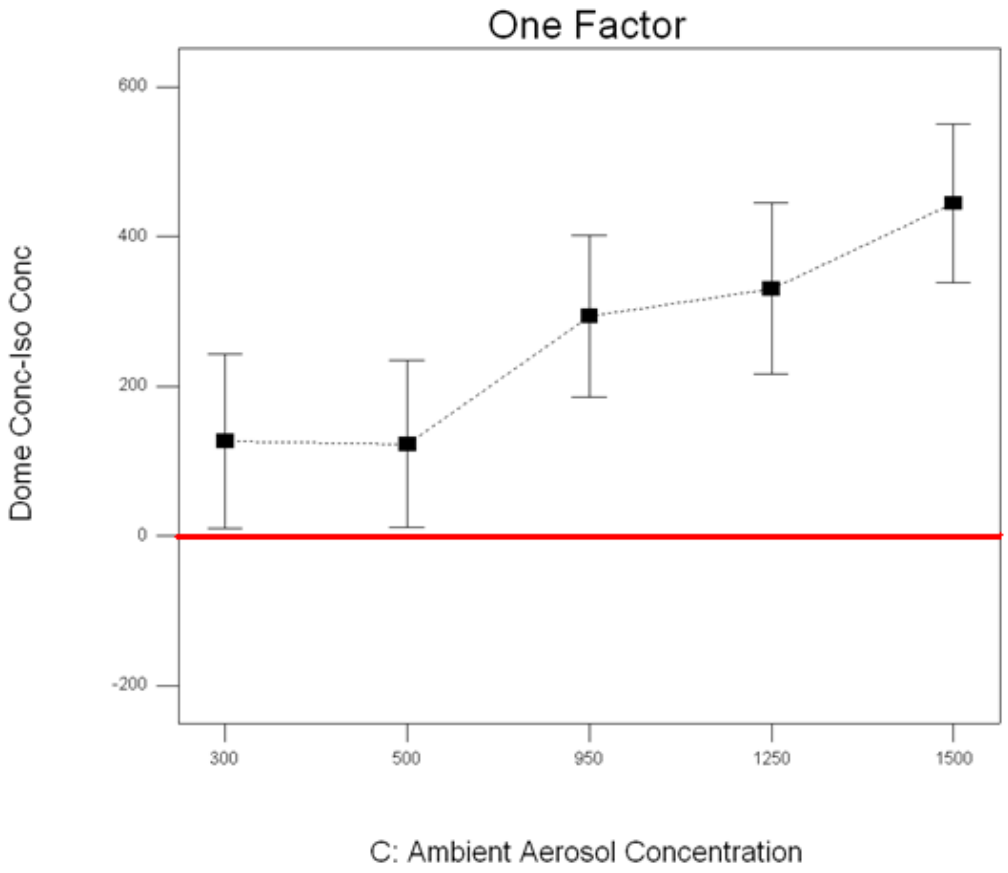

Figure 19. The difference between the concentration measured by the dome TSP sampler and the concentration measured by the isokinetic inlet based on ambient aerosol concentration. The horizontal red line is where the difference between the dome TSP concentration and the isokinetic concentration is zero.

The TSP samplers measured significantly higher concentrations than were measured by the collocated isokinetic sampler. This difference in measured concentration indicates over-sampling by the TSP samplers. This may be due to the

aspiration efficiency of the TSP inlets having a value higher than 1.0. An aspiration efficiency of 1.0 would mean that number of particles in the sampled air was representative of the number of particles in the ambient air, while a value greater than 1.0 would indicate over-sampling. As discussed previously, because the measured MMD and GSD of the TSP inlets were statistically different from the measured MMD and GSD of the isokinetic sampler, the TSP inlets used in this research were not collecting a representative sample of the ambient aerosol present.

Conclusions

For sources of PM to be regulated equitably, the biases and errors associated with the use of FRM PM_{10} samplers must be accounted for and accurately characterized. The use of TSP samplers to characterize the PSD and concentration of ambient dust in a field setting also needs to be fully understood to ensure accurate results.

The results of this study show that both the flat and louvered FRM PM_{10} inlets do not operate within the EPA FRM guidelines for the cutpoint (10 ± 0.5 μm) and slope (1.5 ± 0.1) of PM_{10} samplers when operating in the presence of different poly-disperse dust types, ambient aerosol concentrations, and wind speeds. The cutpoint of both the flat and louvered PM_{10} inlets was significantly higher than the maximum FRM limit of 10.5 μm when sampling dust with higher MMDs than the cutpoint of the sampler, similar to what is emitted from an agricultural operation. The slope values for both the flat and louvered PM_{10} inlets were significantly higher than the maximum FRM limit of 1.6.

Both the cone and dome TSP samplers used in this research did not collect samples of dust that were representative of the ambient aerosol. Because of the difference in sampler performance between the TSP and isokinetic samplers, all concentration values measured by the TSP samplers were significantly higher than the measured isokinetic concentration values.

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 regulations based on dust MMD, ambient aerosol concentration, and ambient wind speed. These consequences may include regulatory fees being placed on industries with dusts that have higher MMDs such as agricultural operations.

CHAPTER V

SUMMARY

Through this research, biases and errors associated with the use of TSP and FRM PM_{10} samplers can be more fully understood. This understanding is essential for equitable regulation of sources of PM. The research presented here investigates if the diurnal change in temperature that may occur during normal sampling of ambient PM affects the sampler flow rate so that it is outside of EPA FRM guidelines for the cutpoint of PM_{10} samplers (10 ± 0.5 μm). Although preliminary calculations showed that the change in sampler flow rate caused by diurnal temperature fluctuations would affect the cutpoint of the FRM PM_{10} sampler, the results of this research prove that this is incorrect. However, ambient wind speed did have an effect on the cutpoint of the samplers operating at different flow rates, causing the difference between the measured sampler cutpoint and the FRM value of 10 μm to decrease as the test wind speed increased. This change was further investigated through continued wind tunnel testing.

Additional wind tunnel testing using two types of TSP and FRM PM_{10} inlets in the presences of three PSDs of dust, three test wind speeds, and five ambient aerosol concentrations provided further insight into sampler performance characteristics. The results of this research showed that the TSP samplers did not collect a representative PSD of ambient aerosols. The measured cutpoints and slopes for both the flat and louvered FRM PM_{10} inlets were not consistently within the EPA FRM guidelines of 10 ± 0.5 μm and 1.5 ± 0.1, respectively. The measured slopes for both the flat and louvered

PM_{10} inlets were significantly higher than the maximum FRM limit of 1.6. The results for cutpoint indicate that as the ambient aerosol concentration and dust MMD increase, the cutpoint of the louvered PM_{10} sampler increases.

The concentration values for all parts of this research were significantly different that the concentration measured by the collocated isokinetic sampler. The concentrations measured in the sampler flow rate study showed that the PM_{10} samplers used consistently over-sampled the ambient PM_{10}. The TSP samplers tested recorded significantly higher concentrations than the isokinetic sampler, with the difference between the measured TSP concentration and the measured isokinetic concentration increasing as the ambient aerosol concentration increased.

The results of this research provide a better understanding of the performance of TSP and FRM PM_{10} samplers operating under different conditions. This research shows that these samplers are not operating as they are designed or intended and industries may be suffering the consequences of inequitable regulations based on dust MMD, ambient aerosol concentration, and ambient wind speed. These consequences may include regulatory fees being placed on industries with dusts that have higher MMDs such as agricultural operations.

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APPENDIX A

TEXAS A&M WIND TUNNEL PERFORMANCE ASSESSMENT TESTS

Velocity Profile

The velocity profile of the sampler test chamber was determined by Chen (2007) using an air velocity transducer (TSI 8455, TSI Inc., Shoreview, MN) with a precision of 0.01 m/s and an accuracy of ± 0.5 percent of full scale of the selected range. The uniformity of wind speed was evaluated by recording wind speeds at all center points along a 16-point (4x4) grid in the test chamber. The grid plane was located at the entrance to the test chamber at the end of the flow-stabilizing duct and had a 1m x 1m cross sectional area. Velocity profile tests were conducted in the same plane in which samplers were located for performance evaluation tests described below.

Velocity uniformity tests were conducted at wind speeds of 2-, 8-, and 24-km/hr, and wind speeds were generated in the same manner used during testing of PM samplers. For velocity uniformity tests at 2 km/hr, the centrifugal fan was turned on and the frequency of the drive increased until the velocity transducer reading was within ± 10 percent of 2 km/hr. The exit exhaust fan was not turned on for the 2 km/hr velocity uniformity tests as it generated wind speeds in excess of 2 km/hr. For each of the 16 grid positions, velocities were recorded every two seconds by the transducer for five minutes and then averaged. At each grid point, the maximum and minimum deviations from the mean velocity were determined. The coefficient of variation (COV) about the mean of all sixteen points was also determined. For velocity uniformity tests at 8- and 24-km/hr, the same procedure was followed with the exception that the exit exhaust fan was operating. For all three tests, the maximum and minimum velocities were found to be within 10 percent of the average velocity at all grid-points. COVs were found to be less than 10 percent for tests at all three wind speeds. The results of the tests showed that the EPA velocity requirements for dust wind tunnels were satisfied for the wind tunnel used in this study (Chen, 2007).

Concentration Profile

Concentration uniformity tests were performed in the wind tunnel to evaluate its conformity to EPA performance specifications for dust wind tunnels (Chen, 2007). Gravimetric sampling with nine isokinetic sampling probes was carried out simultaneously to determine aerosol concentrations at the center points of a 3 x 3 grid that divided the 1 m x1 m flow-stabilizing duct. The isokinetic inlets, designed by Chen (2007), had different opening diameters for the three wind speeds, and were machined conically from aluminum. Isokinetic inlet nozzle diameters of 19.8-, 10.2-, and 7.4-mm were used for sampling at three test wind speeds of 2-, 8-, and 24-km/hr, respectively,

using a sampler flow rate of 1 m^3/hr. The isokinetic samplers utilized 47 mm filters and were connected to stainless steel probes that were fitted into a rack. The rack allowed the sampler grid to be positioned at the entrance of the test chamber. The isokinetic sampling system is described in detail by Chen (2007). The isokinetic samplers blocked 2.7 percent of the vertical cross section of the total sampling area.

The filters used for collecting the sampled dust were 47 mm polytetrafluoroethylene (PTFE) filters (Zefluor PTFE membrane, Pall Corp., East Hill, NY). The filters were weighed on a precision analytical balance (AG 245, Mettler - Toledo Inc., Columbus, OH). For quality control purposes, 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 filter weighing protocol is located in Appendix C.)

Pre-weighed 47 mm PTFE filters were placed in each of the nine isokinetic sampling probes. Concentration tests were performed at the three EPA-specified wind speeds of 2-, 8-, and 24-km/hr with cornstarch. Each isokinetic inlet was connected to a separate low volume sampling system that drew air at a flow rate of approximately 1 m^3/hr. Dust was fed into the wind tunnel at a target concentration of 500 μg/m^3. Test durations for the three velocities were determined in order to collect a minimum of 1 mg of dust on each filter. After each test, the filters were post-weighed and the net difference of weights was divided by the total volume of air sampled to determine TSP concentrations. The COVs of aerosol concentrations for the three wind speeds were less than 10 percent, while the deviation of concentration from the mean was slightly higher than 10 percent for concentration tests at 24 km/hr but below 10 percent for tests at 2- and 8-km/hr (Chen, 2007).

APPENDIX B

DUST PACKING PROCEDURE FOR USE WITH THE BGI WRIGHT DUST FEEDER II

The following procedure was used to pack the dust (Ultrafine Arizona Road Dust, Fine Arizona Road Dust, and Cornstarch) for use with the BGI Wright Dust Feeder II (BGI, 2008).

Procedure

1. If necessary, clean the canister with rubbing alcohol and a paper towel.
2. Break up any clumps in the dust with the spoon.
3. Measure ¼ of a teaspoonful of dust and place it in the canister.
4. Tap the canister on a table to level out the surface of the dust.
5. **Carefully** lower the weight into the canister so that the dust does not get pushed up between the canister and the weight. If dust does get between these two, it will make it very difficult to get the weight out to pack the next layer of dust.
6. Place the canister with the dust and weight in it onto the Arbor Press.
7. Lower the ram of the Arbor Press **slowly** onto the top of the weight in the canister.
8. Use the arm of the Arbor Press to press the dust as much as possible.
9. While applying pressure to the arm of the Arbor Press with one hand, use your other hand to lift the hammer on the top of the Arbor Press about one foot in the air and drop it. Repeat this 20 times.
10. Rotate the canister 180° and repeat steps 7-9 with the canister in this position.
11. Remove the canister from the Arbor Press.
12. Remove the weight from the canister and use the spoon the scrape any excess dust off the sides of the canister and weight.
13. Repeat steps 3-12 until the level of the dust is within ¼ inch of the top of the canister.
14. Place the canister with the weight on top in the center of the hydraulic press. <u>It is important that the canister is in the center of the hydraulic press so that you can remove the weight later</u>.
15. Wrap a towel around the piston of the press to prevent the hydraulic fluid from dripping down and contaminating the dust.

For Ultrafine ARD and Fine ARD: Set the pressure of the hydraulic press to **45 tons** and leave the canister **overnight**.

For Cornstarch: Set the pressure of the hydraulic press to **15 tons** and leave the canister for **30 minutes**.

APPENDIX C

WEIGHING PROCEDURE FOR LOW VOLUME SAMPLER FILTERS

The following procedure was used to weigh the filters used by the low volume samplers. The procedures outlined below are presented in the operating instructions manual for the Mettler – Toledo AG245 balance (Mettler – Toledo, 1994).

Preparing the Filters

Both new and loaded filters must be conditioned in an environmental chamber for 24 hours before weighing with the Mettler-Toledo AG245 balance. The conditions of the air in the chamber must be held at 25°C and 47% relative humidity.

Unloaded (New) low volume sampler filters should be numbered using a permanent marker before weighing.

Low Volume Filters:

a. Write the filter number clearly on one side of the unloaded 47mm diameter filter.
b. Place the newly numbered filter in a new 50mm diameter petri-dish. Do not number the petri-dish.
c. Stack the petri-dishes loaded with numbered filters in order by filter number in stacks of 25.

Calibrating the Scale

Once the scale has been plugged into the electrical wall outlet for 30 minutes, press the <<On/Off>> button to turn the scale on. Calibrate the scale using the following steps.

1. Press and briefly hold (1-2 seconds) the <<1/10d / Cal>> button on the control panel to start the self-calibration routine.
2. The scale will perform the internal calibration routine. The routine is finished once the display message "cal done" appears. If the "abort" message appears during the calibration routine, press the <<C>> button to clear the scale control panel. Repeat step (1) until the calibration routine finishes successfully.
3. Tare the scale readout by pressing the <<O/T>> button.

Weighing a Batch of Filters

1. Open the scale weight spreadsheet on the computer next to the scale table to record the weights into.

2. Enter the number of the filters that are to be weighed into the spreadsheet.
3. Open the balance tray door and place the filter holder apparatus with anti-static tray onto the balance pan.
4. Close the balance tray door.
5. Tare the scale by pressing the <<O/T>> button.
6. Press the <<1/10 d>> button on the scale control panel to add one decimal place to the readout number range.
7. Open the balance tray door and place either the anti-static bag containing the numbered filter (for high volume sampler filter weighing) or the 47mm numbered filter (for low volume sampler filter weighing) on the filter holder apparatus. For low volume sampler filter weighing, weigh only the numbered filter not the filter and petri-dish combined.
8. Once the "o" symbol disappears from the readout, press the <<menu>> button. A three second countdown will begin.
9. Once the countdown has finished, the stable weight will appear on the readout. Record this weight in the spreadsheet.
10. Open the balance tray door and remove the anti-static bag or the low volume filter.
11. Close the balance tray door.
12. Tare the scale by pressing the <<O/T>> button.
13. Repeat steps 7 – 12 for a total of 3 weights before weighing a different filter.
14. Perform the weighing procedure for all of the numbered filters.

Assuring the Quality of the Filter Weights

The standard deviation of the filter weights calculated by the spreadsheet should be less than approximately 30 µg. If the standard deviation of the three weights is above this value, re-weigh the filter until the standard deviation of the three weights is less than 30 µg. If the problem persists the scale may need to be recalibrated or allowed to "warm up" for about 10 minutes before weighing again.

Scale Technical Data

Model: Mettler-Toledo AG245
Readability: 0.01 mg
Max Capacity: 41 g
Repeatability: 0.02 mg
Linearity: 0.03 mg

References

Mettler – Toledo AG. 1994. Operating instructions for Mettler – Toledo AG balances. Greifensee, Switzerland: Mettler – Toledo AG.

APPENDIX D

DUST PARTICLE DENSITY DETERMINATION PROCEDURE

The following procedure was used to determine the particle density of the three dusts used (ultrafine ARD, fine ARD, and cornstarch). The procedures outlined here are presented in the AccuPyc 1330 Pycnometer Operator's Manual (Micromeritics, 2000).

Equipment

1. AccuPyc 1330 Pycnometer (AccuPyc 1330 Pycnometer, Micromeritics Instrument Corp., Norcross, GA)
   Precision: Reproducibility typically to within ±0.01% of the nominal full-scale cell chamber volume. The nominal full scale cell chamber volume is the sample capacity. Reproducibility guaranteed to within ±0.02% of the nominal full-scale volume on clean, dry, thermally equilibrated samples.
   Accuracy: Accurate to within ±0.03% of reading plius 0.03% of the nominal full scale cell chamber volume.
   Sample Volume: 0.5 to 100 cm^3
2. Mettler-Toledo AG245 balance
   Readability: 0.01 mg
   Max Capacity: 41 g
   Repeatability: 0.02 mg
   Linearity: 0.03 mg
3. Calibration Standards
   Two – 23/32" diameter Tungsten Carbide calibration balls calibrated with master balls calibrated by the NIST Test No. 821 25B 592-97 (Precision Ball and Gauge Co., Alvadore, OR).

Calibration Procedure

The pycnometer should be recalibrated anytime it is restarted. The following procedure should be followed to calibrate the pycnometer.

1. Check the calibration of the pycnometer by performing an analysis on the empty sample cup to see how close the average volume is to zero. If the volume returned is not within ±0.05% of full scale, recalibrate the pycnometer using the following procedure.
   When recalibrating the pycnometer, you should set up the calibration parameters so that 10 purges and 10 runs are performed. Perform the procedures in step #8 below before beginning the calibration routine.

2. Place an empty cup in the cell chamber.
3. Replace the cell chamber cap.
4. Press [ ] + [·] to begin the calibration procedure.
5. The following messages will be displayed:
   Volume of cal std: 1.0000 cm^3
   Enter the volume of the calibration standard used and press [ENTER].
   [Enter] to start [Escape] to cancel
   Press [ENTER] to begin the calibration procedure. The pycnometer will beep 3 times once the first phase of the calibration is complete.
   Insert cal std [Enter] to start
   Insert the calibration standard in the cup in the cell chamber. Use both calibration balls for calibrating the 10 cm^3 pycnometer.
6. Replace the cell chamber cap and press [ENTER].
7. During each calibration and analysis procedure, the pycnometer automatically zeros the pressure transducer. This can be done manually by pressing [ ] + [0].
8. Entering the analysis and calibration parameters
   a. Press [ ] + [2] to display and edit the analysis and calibration parameters
   b. Press [CHOICE] until *Analysis Parameters* is displayed and press [ENTER].
   c. Enter the number of purges to be performed (10) and press [ENTER].
   d. Enter the purge fill pressure and press [ENTER]. The purge fill pressure should be 19.5 psig.
   e. Enter the number of runs to be performed (10) and press [ENTER].
   f. Enter the run fill pressure (19.5 psig) and press [ENTER].
   g. Enter the Equilibration Rate (0.005 psig/min) and press [ENTER].
   h. Enter no when asked *"Use run precision?"* and press [ENTER]
   i. Enter the number "0.05" when asked "*Percent full scale?"* and press [ENTER]
   j. Press [SAVE] to save the changes made and return to the display mode.

Performing an Analysis

The cell chamber and cap must be kept clean at all times. Use a lint-free cloth to wipe particles from the surfaces before performing an analysis.

1. Check the helium tank pressure on the regulator to make sure that it is above 200 psig. Lower tank pressures may cause inadequate sample saturation.
2. Set the regulator pressure to 2 psig above the user defined fill pressure for purging and running (see step 8 above). This pressure should be about 21.5 psig.
   a. Press [ ] + [1] to enter manual mode.

   b. Press [8] (expand) and [9] (vent) to open the expansion and vent valves. When the valves are open, the indicators above the keys are turned on.
   c. Press [7] (fill) to open the fill valve.
   d. Set the regulator pressure control knob on the tank to the desired pressure (21.5 psig).
   e. Press [7] (fill) to close the fill valve. Press [SAVE] to return to display mode.
3. Setting report options
   a. Press [ ] + [2].
   b. Press [CHOICE] until *Report Options* is displayed and press [ENTER].
   c. Select density and press [ENTER].
   d. Select Yes for *Request Sample ID?* This option allows the user to enter a sample identification number containing 1 to 20 numbers and dashes.
   e. Press [ENTER].
   f. For *Transmission Format,* select single column.
   g. The *Report Destination* should be set to display. Press [ENTER].
   h. Press [SAVE].
4. Preparing the sample.
   a. Keep the cap on the cell chamber except when actually inserting or removing a sample. If the chamber remains uncapped, temperature instability will occur which could affect analysis results.
   b. Weigh the empty sample cup and record the weight on the log sheet.
   c. Sieve a sample of the dust to be analyzed using a 100 micrometer screen mesh.
   d. Place a quantity of the sample in the sample cup. Use as large a quantity of sample as possible. Try to fill the cup at least two-thirds full. Pack powders and fluffy materials (if permissible) to obtain maximum sample weight in the cup.
   e. Dry the sieved sample in the sample cup according to the procedures outlined in the ASTM Designation: D 3173 – 00 (ASTM, 2000).
   f. Once the sample has been dried and allowed to cool to room temperature in a desiccator, weigh the sample cup containing the dried sample.
   g. Subtract the empty cup weight from the weight of the cup containing the dried sample to obtain the dried sample weight.
   h. Remove the cell chamber cap.
   i. Insert the sample cup with sample into the cell chamber.
   j. Replace the cell chamber cap.
5. Starting the Analysis
   a. To start the analysis press [ ] + [4].
   b. Enter the sample ID and press [ENTER] when prompted.
   c. Enter the dried sample weight when prompted for the sample weight and press [ENTER]. The sample weight should be entered in grams.
   d. Press [ENTER] to begin the analysis.

6. Viewing the Analysis Results
    a. The pycnometer will beep three times when the analysis is complete. Remove the sample from the test chamber and press [CHOICE] to cycle through the error messages.
    b. Once all of the error messages have been displayed, the average density of the user defined number of runs is displayed on the display along with the deviation from the mean. Press [ENTER].
    c. When the *Reload* prompt is displayed, you may begin another operation.

References

Micromeritics Instrument Corp. 2000. AccuPyc 1330 Pycnometer Operator's Manual v3.xx. Norcross, GA: Micromeritics Instrument Corp.

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APPENDIX E

DIFFERENTIAL PRESSURE TRANSDUCER CALIBRATION PROCEDURE

The following procedure was used to determine the differential pressure (in W.C.) vs. output current (ma) for the differential pressure transducers used with the low volume samplers.

Equipment

1. Differential pressure transducer (Omega PX274-30DI, Omega Engineering inc., Stamford, CT)
   Accuracy: ±1% Full Scale (FS) (linearity, repeatability, and hysteresis)
   Operating Temperature: -18 to 80°C (0 – 175°F)
   Media Compatibility: Clean dry air or inert gas
   Environment: 10 to 90% RH non-condensing
   Excitation: 12 to 40 Vdc
   Output: 4 – 20 mA
   Supply Current: 20 mA maximum
   Load Impedance: 1.6 K ohms at 40 Vdc maximum
2. Electrical transformer for differential pressure transducer
3. Fluke multimeter (867B Graphical Multimeter)
   Accuracy: ±0.025% basic accuracy
4. Digital differential pressure gauge (Dwyer Series 475-1 Mark III digital manometer)
   Range: 0 – 19.99 in W.C.
   Accuracy: ±0.5% F.S. (15.6 – 25.6°C), ±1.5% F.S. (0 – 15.6 and 25.6 – 40°C)
5. Digital temperature, barometric pressure, and relative humidity sensor (Davis Perception II)
6. Air pressure generator (Beckman Air Comparison Pycnometer 93001, Beckman Instruments, inc., Irvine, CA)
7. 3 – 2ft pieces of 3/16” ID Tygon tubing
8. 1 - 3/16” OD plastic “T” connector for Tygon tubing
9. Wooden test stand

Procedure

1. Mount the pressure transducer vertically on the test stand with the pressure taps pointing downward.
2. Remove the two screws from the front face of the pressure transducer and pull off the front cover.

3. Connect the pressure generator to the plastic "T" using one piece of the Tygon tubing.
4. Connect one end of the "T" connector to the "+" port of the differential pressure gauge.
5. Connect the open end of the "T" connector to the "+" port of the differential pressure transducer.
6. Locate the "+" and "-" terminals on the differential pressure transducer.
7. Connect the "+" terminal on the pressure transducer to the "+" terminal on the power transformer. Connect the "-" terminal on the pressure transducer to the "-" terminal on the power transformer.
   DO NOT PLUG THE TRANSFORMER INTO THE WALL AT THIS TIME!
8. Connect the multimeter in series with the pressure transducer and power transformer on the "-" side as shown in figure E-1.

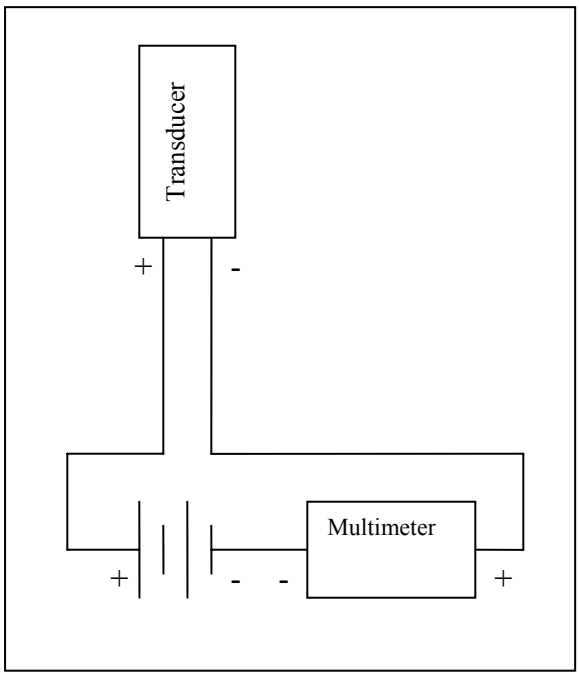

Figure E-1. Wiring schematic for calibrating the differential pressure transducers used with the low volume TSP samplers.

9. Locate the jumper settings for the 0 – 7.5 in W.C. range in the users guide for the PX274 and make sure that the jumpers are set correctly on the differential pressure transducer.
10. Plug the power transformer into the wall electrical outlet.
11. With no pressure applied to the "+" side of the differential pressure transducer, adjust the zero trimmer to obtain the desired low pressure output. The low pressure output should be as close to 4 mA as possible as read by the multimeter set to read in the mA range.

12. Record the low pressure reading from the differential pressure gauge (in W.C.) and the corresponding current output (mA) on the log sheet. Also record the temperature, relative humidity, and barometric pressure from the digital weather station.
13. Turn the knob on the pressure generator until the differential pressure gauge reads 0.5 in W.C. and record the corresponding current output from the differential pressure transducer.
14. Repeat step 13 over the operating range of 0 to 7.5 in W.C.
15. Once all of the differential pressure/output current data points have been taken, input them into a statistical software package (SPSS or SAS) and perform a linear regression analysis on the data. Obtain the linear regression equation coefficients and the coefficient of determination (R^2) from the statistical software output.

APPENDIX F

SHARP-EDGE ORIFICE METER CALIBRATION PROCEDURE

The following procedure was used to calibrate the orifice meters used with the low volume samplers.

Equipment Used

1. Aalborg GFM Mass Flow Meter (GFM373, 0-20 slpm)
   Range: 0 – 20 slpm
   Accuracy: ±1.5% Full Scale (F.S.)
2. Electrical transformer for mass flow meter
3. Fluke multimeter (867B Graphical Multimeter)
   Accuracy: ±0.025% basic accuracy
4. Digital differential pressure gauge (Dwyer Series 475-1 Mark III digital manometer)
   Range: 0 – 19.99 in W.C.
   Accuracy: ±0.5% F.S. (15.6 – 25.6°C), ±1.5% F.S. (0 – 15.6 and 25.6 – 40°C)
5. Digital temperature, barometric pressure, and relative humidity sensor (Davis Perception II)
6. Needle valve
7. Compressed air source
8. 3 - 3 ft pieces of 3/8” diameter plastic tubing
9. 2 – 2 ft pieces of 1/8” diameter plastic tubing
10. 6 steel hose clamps

Setup

1. Connect the needle valve to the compressed air source using one piece of the plastic tubing.
2. Connect the open end of the needle valve to the upstream port on the mass flow meter using a piece of the plastic tubing.
3. Connect the downstream port of the mass flow meter to the upstream port on the orifice meter.
   **The upstream port of the orifice meter is on the side with the pressure tap furthest from the orifice plate*.
4. Plug the electrical transformer for the mass flow meter into the wall outlet and connect it to the mass flow meter.
   **The mass flow meter must be plugged in for 15 minutes before taking flow measurements*.

5. Connect the RS-232 cable to the communication port on the mass flow meter and tighten the holding screws.
6. Connect the multimeter leads to the free ends of the two wires of the RS-232 cable. Turn on the multimeter and set it to read in the 1 volt range.
7. Connect the positive pressure port of the digital manometer to the upstream pressure tap on the orifice meter with a piece of the 1/8" diameter tubing. Connect the negative port to the downstream side with the other piece of 1/8" diameter tubing.

Procedure

1. Record the barometric pressure, temperature, and relative humidity from the Davis Perception II instrument onto the log sheet.
2. With no air flowing through the system, record the voltage from multimeter on the log sheet. This is the "zero flow voltage".
3. Turn on the differential pressure gauge and zero the readout by turning the small steel knob between the pressure ports. Set the readout units to be "in WC" by pressing the E/M button.
4. Turn the knob on the needle valve counter clockwise until the display on the multimeter reads 5.0 ± .05volts.
5. Record the actual voltage and differential pressure on the log sheet.
6. Turn the knob on the needle valve clockwise until the voltage reading is approximately 0.1V less than the previous reading.
7. Record the actual voltage and differential pressure on the log sheet.
8. Repeat steps 6 and 7 until the multimeter reads approximately 2.5 volts.
9. Once all of the readings have been taken, convert the voltage readings to flow readings using equation A-1.

$$Q = 4.0076(V) - 4.0076(V_Z) \qquad \text{(A-1)}$$

where:

Q = standard flow rate (standard liters per minute),
V = voltage reading (volts), and
V_Z = Zero flow voltage (volts).

The standard conditions of the air used by the mass flow meter are 21.1°C and 14.7 PSIA.

10. Calculate the K values for each flow/differential pressure point using equation A-2.

$$K = \frac{Q}{169.2 D_o^2 \sqrt{\frac{\Delta P}{\rho_a}}} \qquad \text{(A-2)}$$

Where:

Do = Orifice diameter (inches),
ΔP = differential pressure (in WC), and

ρ_a = density of standard air (0.075 lb/ft^3), and
169.2 = unit conversion constant.

11. The average of all the K values determined above is the K value for the orifice meter.

APPENDIX G

TEXAS A&M WIND TUNNEL OPERATION PROCEDURE

Preparing to Start

1. Turn on the large switch to the left of the wind tunnel (behind the indoor air quality testing room).
2. Turn the air compressor to 'Auto'. The air compressor is located in a small building near the back fence of the compound.
3. Open the large overhead door of the wood shop. This is necessary due to the large amount of air needed for the main fan of the wind tunnel.
4. Place the filters in the samplers in the test chamber of the wind tunnel and close the door. This door cannot be opened while testing is occurring.
5. Turn on the correct fans for the desired wind speed.
6. Turn on the computer located behind the wind tunnel.
7. Open the LabVIEW program and select the 'Ideal isokinetic sampler 081706.vi' file.
8. View the block diagram of this file to make the appropriate changes for the desired wind speed (see below).
9. From the block diagram, run the LabVIEW program. Click on the 'wire' before and after the calculation of the velocity so that a box pops up.
10. Using the velocity transducer adjust the Zero until the numbers in the two pop up boxes are as close to 0 as possible.
11. Stop the LabVIEW program.

2 km/hr Wind Speed

1. In the block diagram of the LabVIEW program, change:
    a. The isokinetic diameter to **0.78** (middle of the screen)
    b. The Mr equation to read **'Mr = 0.000171*den'** (upper right on the screen)
2. On the front panel of the LabVIEW program, select the isokinetic diameter of **0.78** and the full scale velocity to **1.5**.
3. Set the Full Scale reading on the velocity transducer (mounted on the wind tunnel near the computer) to be the range of **0 – 1.5**.
4. Turn on the mixing fan. This switch is located at the back corner of the wind tunnel on the same side as the computer.
5. Turn on the main fan for the wind tunnel and set the frequency to **6.5 Hz**.

8 km/hr Wind Speed

1. In the block diagram of the LabVIEW program, change:
    a. The isokinetic diameter to **0.40** (middle of the screen)
    b. The Mr equation to read **'Mr = 0.00018*den'** (upper right on the screen)
2. On the front panel of the LabVIEW program, select the isokinetic diameter of **0.40** and the full scale velocity to **2.5**..
3. Set the Full Scale reading on the velocity transducer (mounted on the wind tunnel near the computer) to be the range of **0 – 2.5**.
4. Turn on the mixing fan. This switch is located at the back corner of the wind tunnel on the same side as the computer.
5. Turn on the main fan for the wind tunnel and set the frequency to **16.5 Hz**.
6. Turn on the exhaust fan. This switch is located behind the wind tunnel office on the main floor of the wood shop.

24 km/hr Wind Speed

1. In the block diagram of the LabVIEW program, change:
    a. The isokinetic diameter to **0.29** (middle of the screen)
    b. The Mr equation to read **'Mr = 0.000284*den'** (upper right on the screen)
2. On the front panel of the LabVIEW program, select the isokinetic diameter of **0.29** and the full scale velocity to **7.5**.
3. Set the Full Scale reading on the velocity transducer (mounted on the wind tunnel near the computer) to be the range of **0 – 7.5**.
4. Turn on the mixing fan. This switch is located at the back corner of the wind tunnel on the same side as the computer.
5. Turn on the main fan for the wind tunnel and set the frequency to **60.0 Hz**.
6. Turn on the exhaust fan. This switch is located behind the wind tunnel office on the main floor of the wood shop.

Dust Feeder

1. See the dust packing protocol to determine how to properly pack the dust needed.
2. Using the spreadsheet provided by BGI (http://www.bgiusa.com/agc/wright.htm), determine the correct speed for the concentration desired.
3. Set the recommended dust feeder speed.
4. Set the air pressure to **10-15 psig**.
5. The dust feeder needs to be monitored about every 30 minutes to ensure the dust is still feeding, the air pressure has not caused the line to disconnect, or something else has not gone awry.

Sampler Operation

1. The first sampler to start should always be the isokinetic sampler. Run the LabVIEW program with the appropriate settings for the selected wind speed and save the data file in the location of your choice.
2. Determine the density to use for the sampler boxes by using the density calculated by the LabVIEW program (kg/m^3). To change kg/m^3 to lb/ft^3, divide by 16.01846.
3. Start each of the sampler boxes using the density from step 2. Record the ΔP and the time at the start and end of each test, along with the data from the dataloggers.

APPENDIX H

MALVERN MASTERSIZER 2000 OPERATION PROCEDURE

1. Make sure the instrument is turned on. The switch is on the right side of the Malvern. The blue light on the top right side will come on when the instrument is on. Make sure the computer is connected and turned on.

2. Connect the HYDRO 2000SM (A) unit.
   a. Once the unit is securely in position, the tubing must be connected. For the HYDRO (wet) unit, there are two connection tubes (one is blue and one is red). The two tubes are attached to the SVDU or Small Volume Dispersion Unit. Plug the blue tube into the 'cell out' which has a matching blue outlet. Plug the red tube into the 'cell in' which has a matching red outlet.

3. Begin the program for running samples.
   a. Click on the 'Mastersizer 2000' program icon on the computer's desktop.
   b. The user name should be 'Malvern' and will already be entered. Click 'okay' to continue.
   c. After the 'Tip of the Day' window is closed, a new pop-up window will ask if you want to 'Run an Existing SOP', 'Edit an Existing SOP', 'Use the SOP Creation Wizard', or 'Make a Manual Measurement'.
   d. Choose 'Run an Existing SOP'.
   e. If you 'cancel' out of the pop-up window, use the icons at the top located on the tool bar. Select the 'Run' tab and choose 'Existing SOP'.

4. Choose the 'Mary' SOP (Standard Operating Procedure).

5. Preparing the filter for analysis
   a. Put a small amount of ethanol in a large beaker with the filter to be analyzed.
   b. Place this beaker in the ultrasonic bath for 15 minutes.
   c. Once the 15 minutes has passed, remove the filter from the ethanol.
   d. Pour the ethanol from the large beaker over a 100 μm filter into a smaller beaker.
   e. Use a pipette to dispense the sample into the SVDU when prompted by the SOP as described in the next step.

6. Beginning the SOP
   a. Ensure that there is proper drainage for the ethanol from the SVDU and it does not spill out onto the floor.
   b. Turn on the stirrer in the SVDU to 1250 rpm, as indicated in the SOP.
   c. Clean out the SVDU by pouring in ethanol. Put the handle on the right side of the SVDU up so the ethanol does not drain out. After a few seconds, lower this

handle to drain the ethanol. Repeat this 1 - 2 more times to make sure the SVDU is properly cleaned. The SVDU will need to be cleaned in this manner with ethanol 2 - 3 times before every run to ensure accurate results. The SOP will prompt you to clean it out every time.

d. Select start to begin the background run.
e. Name the samples based on the filter number to be analyzed.
f. The SOP gives instructions in the yellow box that indicates when to add the sample.
g. When the SOP tells you to 'add sample' in the yellow box, add the sample slowly until the blue bar on the screen reaches the green area of the larger bar. Press 'start'. If too much sample is added and the blue bar goes above the green into the red area, start over from step c.
h. Once the analysis is complete, follow the prompts on the computer screen to finish the analysis.
i. Flush the SVDU with ethanol 2-3 times after each run as in the beginning.

7. View results
   a. Highlight the samples to view and select the tab 'Result Analysis (M)'. To view more than one, hold down the shift or control keys to highlight multiple samples.

8. After running samples
   a. The Mastersizer can stay on, as it is built to run nonstop.

9. Exporting files
   a. Highlight the samples to export.
   b. Click on 'File' and 'Export Data'.
   c. A pop-up box will appear. Choose 'Use commas as separators' and 'Include header row' under 'Format Options'.
   d. 'Overwrite' to file means it will completely replace what is currently in the file you are exporting to. 'Append' to file means it will just add what you have selected to the file you are exporting to without replacing what is already there.
   e. Select the location and file name and click 'Export'.

10. Other information:

Cleaning the lenses:

a. The lenses on the insertable unit occasionally have to be cleaned. The program should tell you when it needs to be cleaned.
b. The lenses are cleaned using camera or lens cleaning tissues.
c. The tool to remove the lenses is located on the desk near the SVDU. It is shaped like a hollow cylinder.
d. One end of the tool has two notches in it. Insert the notches into the holes on the sides of the lens and turn it counter-clockwise. Carefully remove the lens and

clean it by gently wiping it with the tissue. Repeat for the lens on the opposite side.

e. After cleaning, gently reinsert the lens into the unit using the tool. Tighten the lens by turning it clock-wise with the tool. DO NOT OVER-TIGHTEN – THIS WILL CRACK THE LENS!

Service and Technical Support:

a. The help desk number for the Malvern is: (800) 932-0101 ext.228
b. If you need to enter formulas for the Malvern to automatically use, call Paul Dawson at (610) 367-4509.
c. The company's email address is: Support@malvernusa.com

Other Settings:

a. The blue bar on the SOP represents the obscuration (range). When running smaller particles (2 micron) you want to keep the obscuration low (1-2%). When running large particles (1000 micron), you can have obscuration limits higher (30%).
b. Make sure you enter a sample name and source type when saving results. You can change the sample name each time, but the source type remains fixed unless you edit the SOP.
c. The Report/Saving tab lets you set up whether you want to automatically export the results of the measurements. You can also change this using 'Edit SOP'.
d. A 10 second background and measurement time should be adequate.

VITA

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Education

Master of Science in Biological and Agricultural Engineering
Texas A&M University (August 2010)
Bachelor of Science in Agricultural Engineering
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Honors

Alpha Epsilon Honor Society
Alpha Zeta Honor Society
Phi Eta Sigma Honor Society
Girl Scout Gold Award

List of Professional Presentations

ASABE Annual International Meeting

- *Evaluation of the TEOM Method for the Measurement of Particulate Matter from Texas Cattle Feedlots*, Providence, RI, June 2008
- *Evaluation of Ambient Particulate Matter (PM) Sampler Performance through Wind Tunnel Testing*, Reno, NV, June 2009
- *Comparison of Measured Concentrations from Collocated TSP, PM_{10}, and $PM_{2.5}$ Samplers in the Presence of Agricultural Particulate Matter*, Reno, NV, June 2009
- *Evaluation of EPA Approved FRM PM_{10} Sampler Performance through Wind Tunnel Testing*, Pittsburgh, PA, June 2010

Beltwide Cotton Conference

- *Evaluations of EPA Approved FRM $PM_{2.5}$ and PM_{10} Samplers*, San Antonio, TX, January 2009, Placed 3rd in Student Presentation Competition
- *PM_{10} Sampler Bias*, New Orleans, LA, January 2010, Placed 2nd in Student Presentation Competition

American Chemical Society

- *Evaluation of EPA Approved FRM PM_{10} Samplers*, Washington, D.C., August 2009