DESIGN OF A HIGH VOLUME PM 2.5 SAMPLER

J.W. McClure, B.W. Shaw and C.B. Parnell, Jr.
Agricultural Engineering, Texas A&M University
College Station, TX

Abstract

The Clean Air Act of 1970 created the National Ambient Air Quality Standards (NAAQS), which regulated Total Suspended Particulates. In 1987 the EPA revised the NAAQS to regulate PM 10 and again in 1997 to include PM 2.5. As a result of a court case the 1997 revision has been remanded back to the EPA because of constitutional questions about EPA's ability to arbitrarily set the NAAQS. The EPA has filed to have the case overturned and the issue is currently in the court system. The outcome is uncertain, but it is evident that a PM 2.5 standard will be implemented. Therefore, it is necessary to determine the PM 2.5 concentrations in the ambient air and from specific sources for both scientific and regulatory purposes. To do this an accurate measure of PM 2.5 is necessary. The existing Federal Reference Method (FRM) sampler has a number of problems that make its usefulness questionable. Most of these problems stem from its low flow rate of 1 m^3/hr (0.6 ft^3/min). This low flow rate brings up questions of how representative the sample is of the ambient air and problems with accurately measuring mass of particulate matter on the filter. There are a number of studies showing that small cyclones can be used to obtain a cutpoint of 2.5 microns at a significantly higher flow rate (68 m^3/hr, 40 ft^3/min) than the existing FRM sampler and other PM 2.5 samplers. Research is in progress to develop and test a cyclone-based sampler at this higher flow rate.

Introduction to the NAAQS

In 1970 congress passed amendments to the Clean Air Act (CAAA) that, along with the National Environmental Policy Act, gave the Environmental Protection Agency (EPA) the authority to regulate air pollution in the United States. The 1970 CAAA also required EPA to set the National Ambient Air Quality Standards (NAAQS). The primary NAAQS was to be based on public health concerns and the secondary standard was based on public welfare (Cooper and Alley, 1994). EPA set the NAAQS for six criteria pollutants, the most important to agriculture being Total Suspended Particulate (TSP).

Congress amended the Clean Air Act in 1977, requiring the EPA to revise the NAAQS every five years. The Act also defined certain classes of areas based on the existing air quality. Class I was defined as pristine areas and Class III as industrialized, Class II being everything else (EPA, 1998). As a result of the 1977 CAAA, EPA revised the NAAQS in 1987. The most important change for agriculture was a new standard for particulate matter (PM) less than 10 microns in aerodynamic equivalent diameter (AED). AED is the diameter of a spherical particle with a density of 1 g/cm^3 that will behave the same, aerodynamically, as the particle in question. This particle size is generally referred to as PM 10. This PM 10 standard replaced the TSP standard.

The Clean Air Act was again amended in 1990. These changes were primarily targeted at urban and global air pollution problems (Cooper and Alley, 1994). Most of these changes did not have a direct effect on agriculture but has and will continue to lead to increased regulation of agriculture. This will primarily be related to the growing belief that in at least some nonattainment areas for PM 10 that much of the particulate matter is from agricultural sources. This is already playing a role in California and some southwestern states.

In 1997, EPA was "forced" to revise the NAAQS after a suit was brought against them by environmental special interest groups. The most potentially important change for agriculture was the addition of PM 2.5 to the NAAQS. During testimony to the Congress's Committee on Agricultural in 1997, Carol Browner, director of EPA, stated, that "EPA does not intend to focus on regulating agricultural tilling to control PM-2.5 and does not believe it would be efficient for states to do so" (Browner, 1997) This is based on the larger size of soil particles and the relatively low release height of tilling operations. It is generally believed that almost all PM 2.5 is secondary PM 2.5, meaning that it is created by chemical reactions of gasses in the air. Sulfates and nitrates produced by combustion are thought to be the primary gasses responsible for secondary PM 2.5. Ammonia has also been implicated in PM 2.5 formation. In Administrator Browner's testimony she also mentions prescribed burning as having a contribution to PM 2.5 and that "… EPA recognizes the role of fire in forest ecosystems and on agricultural lands, and will continue to work with USDA's Forest Service and the Natural Resources Conservation Service to develop air quality strategies that accommodate appropriate uses of burning." This statement leaves open the possibility of regulating prescribed burning operations, which could have significant impacts for some regions.

Carol Browner's testimony indicated that tilling operations should not be of concern with respect to PM 2.5, although PM 10 is another issue, but she fails to address other agricultural sources. There are a number of agricultural sources such as cotton gins, mills, etc. that have the potential to be releasing PM 2.5. In some areas these sources could be relatively significant. She also fails to address potential contributions of secondary PM 2.5 from agricultural traffic and machinery, or from ammonia fertilizers, feeding operations, etc. It may be that they are insignificant sources, but it is to the agricultural communities benefit to be aware of their emissions and any potential regulatory actions directed towards it.

Federal Reference Method Sampler

Measuring PM 2.5 in the ambient air is a challenging problem. When the 1997 revisions to the NAAQS were passed, a Federal Reference Method (FRM) sampler was specified for use in regulatory monitoring. This FRM sampler is an impaction device that was specified "by design" (EPA, 1997). This means that the imapactor used is specified by its design, not performance characteristics. As long as the impactor is of the appropriate dimensions and materials then it is allowed.

This design specification allows for some flexibility in all aspects of the sampler except for the impactor. Therefore all samplers used to determine attainment status must utilize the same impactor design and must be operated at the same parameters. This makes EPA's job of approving samplers easier, but it does not allow for much flexibility, and there are some questions of accuracy of the FRM sampler that will be addressed later.

There are performance requirements for other aspects of the sampler, most of which are based on the need to control the sampler flow rate. The design specification, rather than a performance one, is based on the idea that if the impactor is built to the exact specifications of the original, tested impactor, then it should perform the same as long as the flow rate is maintained. Tests to ensure that the sampler performs similar to the original FRM sampler are required, but no tests are required to determine the actual performance of the sampler compared to how it should be theoretically performing (EPA, 1997). That is with a cutpoint of 2.5 μm and a slope of nearly 1. Which means that it is collecting nearly all of the particles less than 2.5 μm and none of the particles greater than 2.5 μm.

The impactor used in the FRM sampler is a Well-type Impactor Ninety Six (WINS). The FRM sampler also includes a impaction device as a PM 10 preseperator.

Impaction has been used for several decades as a method of obtaining "cuts" when sampling and sizing particulate matter. There have been a number of documented problems with jet impaction. These problems include particle bounce and reentrainment, overloading of the impaction plate. The WINS impactor has been tested and shown to have a reasonably good cutpoint (2.5 to 2.7) and slope (1.18 to 1.38) (Buch, 1999).

The primary problem with the FRM sampler is its relatively low flow rate. The design low rate for the FRM sampler is 16.67 L/min or about 1 m^3/hr. If a 24 hour sample was taken in an area where the PM 2.5 concentration is 65 $\mu g/m^3$, which is the 1997 NAAQS for PM 2.5, the total weight on the filter would be 1.56 mg. This PM mass is difficult to detect relative to the filter weight. Very sensitive (and expensive) scales are needed to be able to accurately measure the PM.

Because there is very little mass on the filter, handling can also play a large part in the accuracy of the measurement. Touching or handling the filters can lead to significant contamination of the filter. Also, if a filter is dropped, or even bumped, then particles can be lost. Particles can also fall on the filter during handling which can lead to significantly higher mass measurements. Even when QA/QC protocols are followed contamination can easily have an effect.

The low flow rate also forces samples to be of a longer time period, at least 24 hrs. Many research and modeling projects require shorter sampling times for a number of reasons. The FRM sampler does not really allow for shorter sampling times because the amount of mass on the filter would be nearly undetectable.

All of these problems show that the accuracy of the FRM PM 2.5 sampler is questionable and that alternatives should be looked at. Of course, the FRM sampler is only required for primary NAQQS compliance monitoring. Other samplers can be used in other areas. These may include scientific studies and visibility studies in Class I areas (national parks) (EPA, 1997). Although, these samplers also suffer from the problems associated with a low flow rate.

Cyclone Samplers

Due to the problems of measuring small quantities of particulate matter on a filter, a method of obtaining higher quantities of PM while maintaining the necessary cutpoint of the sampler and filter characteristics is needed. There are a number of methods to obtain the proper cutpoint but only centrifugal devices such as cyclones can offer the flow rates needed to obtain a significant mass of PM 2.5 on the filter.

Cyclones have been used for many years as sampling devices. They are simple to design and operate and there is a large body of literature supporting their effectiveness as sampling devices. Cyclones are regularly used in personal air samplers and have been shown to be able to obtain cutpoints around 2.5 μm. These personal samplers are generally low flow rate samplers designed to mimic what would actually be inhaled by those wearing them. This low flow rate causes them to suffer from the same potential problems as those of the FRM sampler.

The IMPROVE sampler, which is based on a cyclone preseperator, is used for ambient monitoring in CLASS I areas. It also has a low flow rate and therefore will have the same mass measurement problems.

The amount of mass captured on the filter is a function of both the concentration of dust in the air and the flow rate of the sampler. The ambient concentration is the desired measurement, therefore it is necessary to control the flow rate of the sampler in order to obtain the minimum mass that can be measured. Our studies and others have shown that small cyclones operated at higher flow rates are capable of obtaining a 2.5 μm cut. At a flow rate of around 1132.8 L/min (40 ft^3/min) it is possible to obtain 2.5 μm cut. If a sample were taken at the same conditions described before, then a total of 106 mg of PM would be captured on the filter (compared to 1.6 mg). This amount is much easier to measure accurately and does not require specialized equipment. The larger mass also reduces the chances of significant contamination by increasing the sample to noise ratio.

High Volume Sampler Design

From the above discussion it can be seen that a better sampler is needed for collecting PM 2.5. The primary problem has been the flow rate of the sampler. Therefore, we are currently developing a high volume PM 2.5 sampler that will sample around 1132.8 L/min (40 ft^3/min). There are a number of steps in this process and problems associated with each so we will discuss them separately.

Design Characteristics

Unlike the FRM PM 2.5 sampler, our high volume sampler will be a performance based sampler, therefore it is necessary that certain performance characteristics be determined before the design of the sampler is really begun. These performance characteristics are based on the final accuracy of the sampler at measuring PM 2.5 under varying conditions. The two principle characteristics in question are the cutpoint and slope of the sampler collection efficiency curve.

The collection efficiency curve is the curve showing the efficiency of the device at collecting each size particle. It is typically plotted on a log-normal graph. An ideal PM 2.5 preseperator of a sampler would have a cutpoint of 2.5 μm and a slope of 1.This means that it would collect all of the particles greater than 2.5 μm and allow all those less than 2.5 μm to pass on to the filter. In reality this is not possible therefore the goal is to obtain a slope as close as possible to 1 while maintaining the cutpoint at 2.5 μm.

Because it is not possible to have a perfect sampler, certain allowable deviations must be determined that will yield sufficient flexibility in design and operation, but not compromise the accuracy significantly. To do this a desired accuracy and precision must be determined. This will be based on the final measurement of mass on the filter. This mass must be close to the desired mass (if the sampler were ideal) within a certain range, say ±5%. This range would then guide the rest of the sampler design.

With this range set we can then set a limit on the range for the cutpoint and slope. A range of cutpoints and slopes can be chosen, and through calculations, this range can be narrowed or broadened until the mass range can be met. This is done by arbitrarily picking a range of cutpoints, say 2.5±0.5 μm, and a range of slopes, say 1.5±0.5. Then calculations would be done using various combinations of these applied to a certain particle size distribution (PSD) of the theoretical ambient air. Various PSDs would need to be used in order to insure that the sampler is robust enough to handle all situations it may be faced with, or to determine situations in which it cannot be used.

Once the cutpoint and slope limits have been determined, design and operating parameters can be set. The slope will guide the shape of the cyclone since certain cyclones are known to have sharper cutpoints (i.e. closer to 1) than others.

Design Flow Rate

As mentioned above, the design flow rate for the sampler will be around 1132.8 L/min (40 ft^3/min). This flow will yield high enough amounts of PM on the filter to be easily weighed and more difficult to contaminate. The actual flow rate will be determined by the size of the dimensions of the sampler and the necessary velocity to obtain the 2.5 μm cutpoint. The flow rate will also be controlled by the filter media chosen. If the pressure caused by the filter is to high then modifications to the filter or sampler will have to be made. This will be discussed more later.

In order to maintain the cutpoint within limits it is crucial that the flow rate be maintained at or very near the design point. Tests will be conducted to determine how much variation in flow is allowable to keep the sampler within the desired performance characteristics. This will determine the operating parameters and a system will be designed that will control the flow rate within the given range.

Filter Selection

EPA requires a Teflon membrane filter to be used in the FRM sampler. While we are not attempting to gain FRM status we believe that a filter with similar characteristics should be used. The reason for this is that Teflon produces less contamination when the filter is being used for particle sizing and it is generally less reactive than most other filter types.

The type of Teflon filter used in the FRM sampler is a membrane type filter. The filter is a thin sheet of Teflon stretched across a ring. The filter has microscopic holes punched in it to allow air flow. These filters do not work well for particle sizing because they deform when cut. Another problem with the filter is its high flow resistance. In order to obtain the desired flow rate a large filter would need to be used to minimize the pressure drop. To reduce these problems a different type of filter will be considered.

Several styles of filters are available. One will be chosen based on its ability to be used for particle sizing, reactivity, particle collection efficiency, and pressure drop. All of these characteristics will be considered before the selection will be made and tests will be run before making a final selection.

Monitoring System

EPA requires a monitoring system to keep track of the basic meteorological conditions such as temperature and pressure of the ambient air. There are also requirements for the temperature of the sample relative to the ambient temperature. All of the operating parameters must be able to be reported to the operator.

While this is required only of samplers which are candidates for FRM approval, we believe these standards should also be incorporated into our sampler. This is both for potential future approval if the regulations are changed, but also because it is generally information that the operator will need to know and will usually obtain from another source anyway.

References

Browner, C.M. 1997. Testimony before Committee on Agriculture, United States House of Representatives. September 16.

Buch, U.M. 1999. Performance Analysis of the Cascade Impactor, The Federal Reference Method PM 2.5 Sampler, and the IMPROVE PM 2.5 Sampler. M.S. Thesis. Texas A&M University, College Station, TX.

Cooper, C.D. and F.C. Alley. 1994. *Air Pollution Control: A Design Approach. 2nd Edition*. Prospect Heights, Illinois: Waveland Press, Inc.

Environmental Protection Agency. 1997. 40 CFR Part 50, National Ambient Air Quality Standards for Particulate Matter; Final Rule. July 18.