The Society for engineering in agricultural, food, and biological systems

*An ASAE Meeting Presentation*

*Paper Number: 054046*

# Particle Size Distribution in the Downwind Plume and Its Impact on Ambient $PM_{10}$ Monitoring for Agricultural Emissions

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**Written for presentation at the**
**2005 ASAE Annual International Meeting**
**Sponsored by ASAE**
**Tampa Convention Center**
**Tampa, Florida**
**17 - 20 July 2005**

***Abstract.*** *Particle size distribution (PSD) in the downwind plume was analyzed for the study of its impact on ambient particulate matter (PM) monitoring. PSD in the downwind plume varies due to the gravitational settling. Gravitational settling has greater impact on downwind PSD to those source PSDs with larger mass median diameter (MMD). The change of PSD is a function of source PSD of*

*PM emitted, wind speed, and downwind distance. Both MMD and geometric standard deviation (GSD) in the downwind plume decrease with increase of downwind distance and source MMD. The larger the MMD of the source, the greater the change of MMD and GSD in the downwind plume. Also, the longer the distance, the greater change of MMD and GSD in the downwind plume.*

*Variations of PSD in the downwind plume have significant impact on $PM_{10}$ sampling errors associated with EPA $PM_{10}$ sampler. The $PM_{10}$ over-sampling rate increases with increase in downwind distance caused by the decrease of GSD of PSD in the downwind plume. Gravitational settling of particles does not help reduce over-sampling from problems associated with EPA $PM_{10}$ sampler. Over-sampling rates decrease with increase of the wind speed.*

**Keywords.** Particulate matter, particle size distribution, mass median diameter, geometric standard deviation, downwind plume, gravitational settling. $PM_{10}$ over-sampling

## Introduction

National Ambient Air Quality Standards (NAAQS) have been used to regulate criteria pollutants emitted by industries including agricultural operations such as cotton gins, grain elevators, and animal feeding operations. Moreover, some State Air Pollution Regulatory Agencies (SAPRA's) apply the NAAQS as property line concentration limits to regulate emissions. $PM_{10}$ and $PM_{2.5}$ are indicators of particulate matter (PM) pollutants (U.S. EPA, 40 CFR50, 2000) listed in the NAAQS. By definition, $PM_{10}$ and $PM_{2.5}$ are particles with an aerodynamic equivalent diameter (AED) less than or equal to a nominal 10 and 2.5 μm, respectively. The regulation of PM is based upon the emission concentration of $PM_{10}$ and $PM_{2.5}$ measured by Federal Reference Method (FRM) $PM_{10}$ and $PM_{2.5}$ samplers at property line The FRM performance standard for samplers is a cut-point of 10 ± 0.5 μm with a slope of 1.5 ± 0.1 (U. S. EPA 40CFR53, 2000). Buser et al. (2001) reported that $PM_{10}$ sampler measurements might be 139 to 343% higher than the true $PM_{10}$ concentration if the pre-collector of sampler operates within the designed FRM performance standards sampling PM having a particle size distribution (PSD) with a mass median diameter (MMD) of 20 μm and geometric standard deviations (GSD) of 2.0 and 1.5, respectively. The research results indicated inherent $PM_{10}$ sampling errors associated with $PM_{10}$ and $PM_{2.5}$ samplers. The inherent sampling errors are due to the interaction of particle size and sampler performance characteristics. It is very important to characterize PSD of PM in the air at property line for understanding and correcting $PM_{10}$ sampler's inherent sampling errors. The goal of this research is to quantify the impact of particle gravitational settling on PSD in downwind plume that would be captured on a total suspended particles (TSP) sampler at property line.

Besides using $PM_{10}$ sampler measurement, SAPRA's also utilize dispersion modeling process to regulate PM emission. In this process, EPA approved dispersion-modeling predictions of $PM_{10}$ and $PM_{2.5}$ concentrations at property line are used to permit operations in compliance with NAAQS limits at property line or to deny operations exceeding the NAAQS at property line.

### *Ambient PM Particle Size Distribution*

To accurately predict downwind PM concentration, dispersion models need to account for changes of PSD in the downwind plume due to gravitational settling of large particles

PSD is one of the most important characteristics of suspended particles in the air. Hinds (1999) stated that lognormal distribution was used extensively for aerosol size distributions because it fitted the observed size distributions reasonably well. A lognormal distribution, which is normal distribution with respect to $\ln(d_p)$, can be characterized by two parameters: MMD and GSD. A cumulative normal distribution $F_x$, gives the mass fraction of all the particles with diameters less than X. It is another way to characterize particle size distribution. Theoretically; the cumulative distribution function is (Hinds, 1999):

$$F_x = \int_0^x \frac{1}{\sqrt{2\pi} * d_p * \ln(GSD)} \exp\left[\frac{-\left(\ln d_p - \ln(MMD)\right)^2}{2\left(\ln(GSD)\right)^2}\right] dd_p = F\left(d_p, MMD, GSD\right) \quad (1)$$

The GSD is a dimensionless quantity with a value greater than 1.0. It is defined by (Hinds, 1999):

$$GSD = \frac{d_{84.1}}{MMD} = \frac{MMD}{d_{15.9}} = \left( \frac{d_{84.1}}{MMD} \right)^{1/2} \tag{2}$$

where:

$d_{84.1}$ = diameter where particles constituting 84.1% of total mass of particles that are smaller than this size,

MMD = mass median diameter of PSD, and

$d_{15.9}$ = diameter where particles constituting 15.9% of total mass of particles that are smaller than this size.

### *$PM_{10}$ Sampler Errors*

Buser et al. (2001, 2002, and 2003) first defined EPA approved ambient air sampler errors due to the interaction of PSD and sampler performance characteristics as:

$$OR = \left( \frac{Measured}{True} - 1 \right) = \frac{(PM_{10} / TSP)_{measured}}{(PM_{10} / TSP)_{true}} - 1 \tag{3}$$

$$E(MMD, GSD, d_{50}, slope) + 1 = \left[ \frac{\int_0^\infty f(d_p, MMD, GSD) P_m(d_p, d_{50}, slope)\, dd_p}{\int_0^{d_{50}} f(d_p, MMD, GSD)\, dd_p} \right] \tag{4}$$

In equation 4:

- *$E(MMD, GSD, d_{50}, slope)$* is the over-sampling rate (OR) of the $PM_{10}$ sampler, which is caused by the interaction between PSD of the PM (characterized by MMD and GSD) and the sampler performance characteristics (characterized by cut-point, $d_{50}$, and slope).
- *$f(d_p, MMD, GSD)$* is the mass density function of PSD, which follows a lognormal distribution function defined by MMD and GSD of the PM.
- *$P_m(d_p, d_{50}, slope)$* is the sampler penetration efficiency curve defined by its cut-point ($d_{50}$) and slope. $P_m$ follows a cumulative lognormal distribution function defined by sampler's $d_{50}$ and slope. The cut-point ($d_{50}$) of a sampler is the particle size, at which 50% collection efficiency occurs and the slope of a sampler is the sharpness of the sampler fractional collection efficiency curve.
- The FRM performance standards for $PM_{10}$ sampler:

  $d_{50} = 10 \pm 0.5\ \mu m$, slope = $1.5 \pm 0.1$

Equation 4 is the governing equation to theoretically evaluate the impact of PM PSD in the downwind plume on over-sampling problems associated with EPA $PM_{10}$ sampler.

## Change of PSD in the Downwind Plume

It has been reported (Wang et al., 2005) that there are significant variations in PSD of PM in the downwind plume due to gravitational settling. The change of PSD in the downwind plume is a function of source PSD, wind speed, and downwind distance.

A cotton gin is used as an example to analyze the change in PSD of PM in the downwind plume due to particle settling. Particle settling trajectory is shown in figure 1. The particle horizontal terminal settling distance $X_{TS}$ is determined in equation 5 (Wang et al., 2005):

$$X_{TS} = \frac{h + \Delta h}{V_{TS}} * U \tag{5}$$

where

$X_{TS}$ = particle horizontal settling distance (m),
$h$ = stack physical height (m),
$\Delta h$ = plume rise (m) determined by the Holland formula (Cooper and Alley, 1994),
$U$ = wind speed (m/s), and
$V_{TS}$ = particle terminal settling velocity (m/s) determined by Stoke's Law.

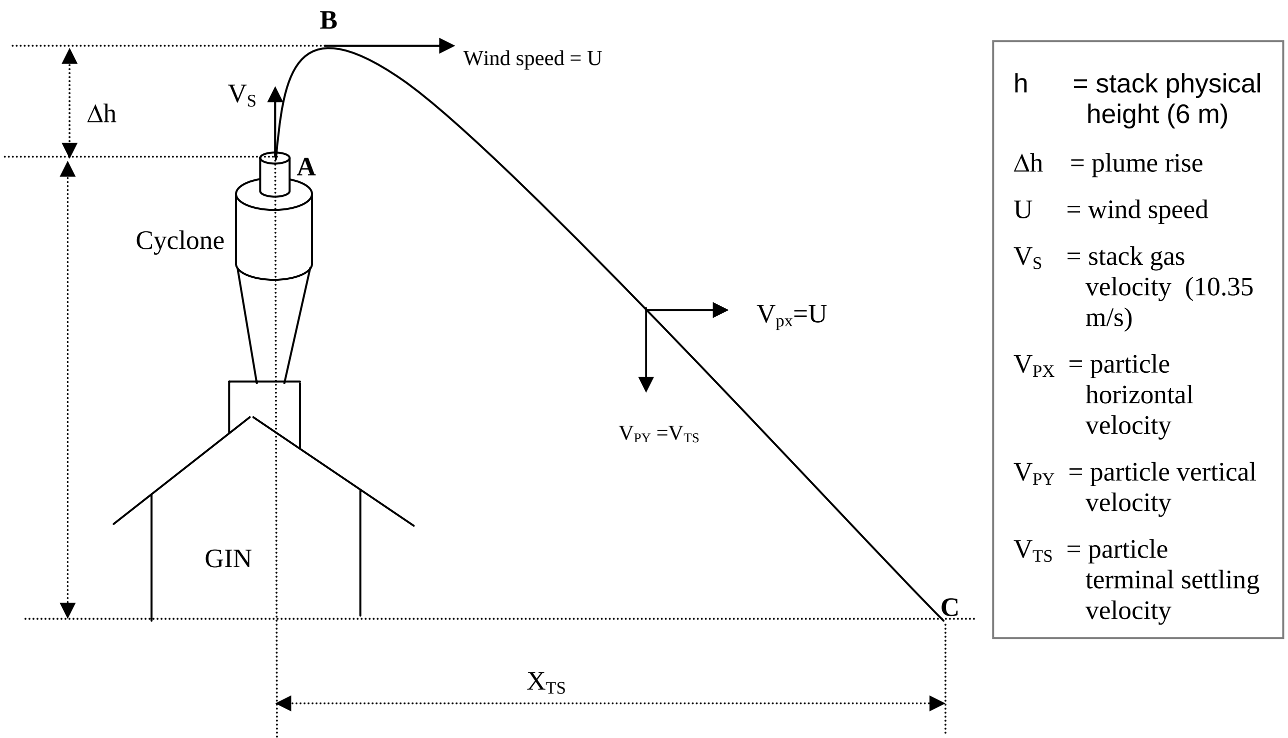


Figure 1. Diagram of particle settling trajectory

It is assumed that once a particle travels to its horizontal terminal settling distance $X_{TS}$, then this particle is removed from the plume. The change of PSD in the downwind plume is determined through the following process:

1. Use equation 5 to calculate particle horizontal travel distance before it is removed from the plume by gravitational settling,
2. Subtract mass fraction of deposited particles from source PSD to obtain changed PSD at any given distance $X_1$. The deposited particles are defined as those particles whose horizontal settling travel distance ($X_{TS}$) is less than $X_1$ ($X_{TS}$<$X_1$),
3. Normalize changed PSD to obtain new PSD in the downwind plume at distance $X_1$, using equation 6:

$$F_d = \frac{\int_0^d \frac{1}{\sqrt{2\pi} * d_p * ln(GSD)} exp\left[\frac{-(ln\, d_p - ln(MMD))^2}{2(ln(GSD))^2}\right] dd_p}{\int_0^{d_{TS}} \frac{1}{\sqrt{2\pi} * d_p * ln(GSD)} exp\left[\frac{-(ln\, d_p - ln(MMD))^2}{2(ln(GSD))^2}\right] dd_p} \qquad (6)$$

where

$F_d$ = the mass fraction of all the particles with diameters less than d, new cumulative PSD

MMD = mass median diameter of source PSD,

GSD = geometric standard deviation of source PSD, and

$d_{TS}$ = smallest particle diameter at which, the horizontal settling distance is less than $X_1$

4. Based upon new PSD ($F_d$), new MMD' is obtained and equation 2 is used to determine new GSD',

5. Repeat steps 1 through 4 to obtain PSD in the downwind plume at distance $X_2$, $X_3$, ............

## Results and Discussion

It has been reported that typically, agricultural dust has approximate MMD of 20 μm, GSD of 2 (Parnell et al., 2003). In this research, three source PSDs (MMD=10, 15, 20 and GSD=2), three wind speeds (0.5, 3, and 6 m/s) were used as a case study to predict PSD in the downwind plume at distances of 100m, 300m, and 500m. Table 1 summarizes the predicted PSD (MMD' and GSD') in the downwind plume. The results in this table indicate that both MMD and GSD decrease with increase of downwind distance due to gravitational settling. Wind speed, downwind distance and source PSD (MMD and GSD) have significant impact on the change of MMD and GSD in the downwind plume.

Table 1. Change of PSD in the downwind plume due to gravitational settling

| *Source PSD: MMD=10 μm, GSD=2* | | | | | | |
|---|---|---|---|---|---|---|
| Wind speed | 0.5 m/s | | 3 m/s | | 6 m/s | |
| Distance | MMD (μm) | GSD | MMD (μm) | GSD | MMD (μm) | GSD |
| 100 m | 9.90 | 2.00 | 10.00 | 2.00 | 10.00 | 2.00 |
| 300 m | 9.60 | 1.92 | 9.90 | 1.98 | 10.00 | 2.00 |
| 500 m | 9.30 | 1.76 | 9.80 | 1.94 | 9.90 | 1.98 |
| *Source PSD: MMD=15 μm, GSD=2* | | | | | | |
| Wind speed | 0.5 m/s | | 3 m/s | | 6 m/s | |
| Distance | MMD (μm) | GSD | MMD (μm) | GSD | MMD (μm) | GSD |
| 100 m | 14.70 | 1.94 | 15.00 | 1.99 | 15.00 | 2.00 |
| 300 m | 13.40 | 1.75 | 14.60 | 1.90 | 14.80 | 1.96 |
| 500 m | 12.30 | 1.59 | 14.00 | 1.81 | 14.60 | 1.90 |
| *Source PSD: MMD=20 μm, GSD=2* | | | | | | |
| Wind speed | 0.5 m/s | | 3 m/s | | 6 m/s | |
| Distance | MMD (μm) | GSD | MMD (μm) | GSD | MMD (μm) | GSD |
| 100 m | 19.00 | 1.84 | 19.80 | 1.94 | 20.00 | 1.98 |
| 300 m | 16.30 | 1.58 | 18.70 | 1.79 | 19.50 | 1.89 |
| 500 m | 14.40 | 1.46 | 17.50 | 1.67 | 18.70 | 1.80 |

For source PSD of MMD=10μm and GSD=2, at wind speed of 0.5m/s, MMD changes from 10 μm to 9.3 μm, GSD changes from 2 to 1.76 at 500 m downwind, whereas, at wind speed of 6m/s, MMD changes from 10 μm to 9.9 μm, GSD changes from 2 to 1.98. The higher the wind speed, the smaller the change of MMD and GSD.

Gravitational settling has greater impact on downwind PSD to source PSD with larger MMDs. At wind speed of 0.5 m/s and 500m downwind distance, MMD and GSD change from source of 10 μm in MMD and GSD of 2 to MMD of 9.3 μm and GSD of 1.76 versus change from source of 20 μm and GSD of 2 to 14.4 μm in MMD and 1.46 in GSD. Both MMD and GSD decrease with increase of downwind distance.

Equation 4 was used to theoretically quantify the impact of downwind PSDs on $PM_{10}$ over-sampling rates associated with EPA $PM_{10}$ sampler. The results of this analysis are listed in table 2. Previous research (Buser et al., 2001) suggested that $PM_{10}$ sampler inherent sampling error is a function of PSD in the air. The larger MMD, the larger the sampling error for a given GSD. From results of change in MMD in the downwind plume, it seems that particle settling mechanism could reduce $PM_{10}$ sampler's inherent sampling error by placing the sampler at a distance such that the larger particles have settled out. However, GSD has significant impact on $PM_{10}$ sampling error as well. The smaller GSD will introduce larger sampling error. $PM_{10}$ sampler sampling error is more sensitive to GSD than to MMD. Results in table 2 suggest that for a given emission source and wind speed, the over-sampling rate increases with increase of downwind distance. It is caused by the decrease of GSD of PSD in the downwind plume. Over-sampling rates decrease with increase of the wind speed.

Table 2. Impact of PSD in the downwind plume on $PM_{10}$ over-sampling rate (%) – EPA $PM_{10}$ sampler errors (determined using equation 4 for $PM_{10}$ sampler with $d_{50}$ = 10 μm and slope = 1.5)

| Source PSD | MMD=10 μm, GSD=2 | | | MMD=15 μm, GSD=2 | | | MMD=20 μm, GSD=2 | | |
|---|---|---|---|---|---|---|---|---|---|
| Wind speed | 0.5 m/s | 3 m/s | 6 m/s | 0.5 m/s | 3 m/s | 6 m/s | 0.5 m/s | 3 m/s | 6 m/s |
| at source | 0% | 0% | 0% | 9.9% | 9.9% | 9.9% | 22.3% | 22.3% | 22.3% |
| at 100 m | -0.2%[1] | 0% | 0% | 10.5% | 11.3% | 9.9% | 30.2% | 25.3% | 23.4% |
| at 300 m | -0.7% | -0.2% | 0% | 11.8% | 11.3% | 10.3% | 48.6% | 33.8% | 27.9% |
| at 500 m | -1.7% | -0.4% | -0.2% | 12.4% | 12.1% | 14.3% | 52.4% | 42.5% | 32.7% |

[1] Negative over-sampling rate indicates under-sampling.

## Conclusion

Particle size distribution (PSD) in the downwind plume was analyzed for the study of its impact on ambient particulate matter (PM) monitoring. PSD in the downwind plume varies due to the gravitational settling. Gravitational settling has greater impact on downwind PSD to those source PSDs with larger mass median diameter (MMD). The change of PSD is a function of source PSD of PM emitted, wind speed, and downwind distance. Both MMD and geometric standard deviation (GSD) in the downwind plume decrease with increase of downwind distance and source MMD. The larger the MMD of the source, the greater the change of MMD and GSD in the downwind plume. Also, the longer the distance, the greater change of MMD and GSD in the downwind plume.

Variations of PSD in the downwind plume have significant impact on $PM_{10}$ sampling errors associated with EPA $PM_{10}$ sampler. The $PM_{10}$ over-sampling rate increases with increase in downwind distance caused by the decrease of GSD of PSD in the downwind plume. Gravitational settling of particles does not help reduce over-sampling from problems associated with EPA PM10 sampler. Over-sampling rates decrease with increase of the wind speed.

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