Dry Deposition of Particulate Matter Emitted from Cotton Gins - Particle Size Distribution of the Particulate Matter in the Downwind Plume

Lingjuan Wang, Calvin B. Parnell, Jr., Bryan W. Shaw, Ronald E. Lacey, Sergio C. Capareda
Center for Agricultural Quality Engineering and Science (CAAQES)
Department of Biological and Agricultural Engineering
Texas A&M University, College Station, TX77843-2117

Abstract

An engineering approach to analyze PM dry deposition due to gravitational settling is summarized in this paper. Particle horizontal settling distance is determined based upon wind speed and particle terminal settling velocity. New PSD in the downwind plume is calculated based upon particle horizontal settling distance and source PSD. Results of this research indicate that change of PSD in the downwind plume is a function of wind speed, downwind distance and source PSD. Both MMD and GSD in the downwind plume decrease with increase of downwind distance and source MMD. When the MMD of the source is high, there was a big change in the MMD and GSD of the dust in the downwind plume. Likewise, there was a big change in the MMD and GSD of dust in the downwind plume as downwind distance is increased. However, the change of wind speed has an inverse impact on the change of downwind PSD. MMD and GSD in the downwind plume decrease with decrease of wind speed. Gravitational settling causes significant change of MMD and GSD in the downwind plume and thus, has significant impact on the PM$_{10}$ sampling error problems. Future research is needed to quantify this impact for more accurate PM$_{10}$ measurement

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, 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$_{25}$ are indicators of particulate matter (PM) pollutants (U.S. EPA, 40 CFR50, 2000) listed in the NAAQS. By definition, PM$_{10}$ and PM$_{25}$ 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$_{25}$ 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 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 studying and correcting PM$_{10}$ sampler's inherent sampling errors. The goal of this research is to quantify 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 in exceedance of the NAAQS at property line. To accurately predict downwind PM concentration, dispersion models also 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 form of particle size distribution. Theoretically; the cumulative distribution function is presented as (Hinds, 1999):

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

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

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

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.

Analysis of PM Dry Deposition Due to Gravitational Settling

According to Hinds (1999), most aerosol motion occurs at low Reynols number (Stoke's region) due to the low velocities and small particle size. Thus, Stoke's law is applied to determine the velocity of particle undergoing gravitational settling. To characterize the PSD of PM (in the downwind plume) emitted from cotton gins, the following assumptions are involved in this study:

1. Particles are spherical. Aerodynamic equivalent diameter (AED) of particle is used to standardize for shape (a sphere) and density (1000kg/m^3).
2. Particle AED >1 µm, the coefficient of drag CD=1(no slip correction needed)
3. Wind speed is constant along particle settling trajectory
4. All particles will deposit at their horizontal settling distance X_{TS}

Figure 1 illustrates particle-settling trajectory. A cotton gin is used as an example to describe analysis of particle dry deposition due to gravitational settling. In this cotton gin, 1D3D cyclones - 0.9 meter (36 inch) in diameter are used as PM abatement device. The height of cyclone exit is 6 meter. Cyclones operate at design inlet velocity of 16 m/s (3200 ft/min.). The airflow at cyclone outlet is 10.35 m/s based upon cyclone design. It is assumed that the particle velocity at cyclone exit will be the same as air flow velocity.

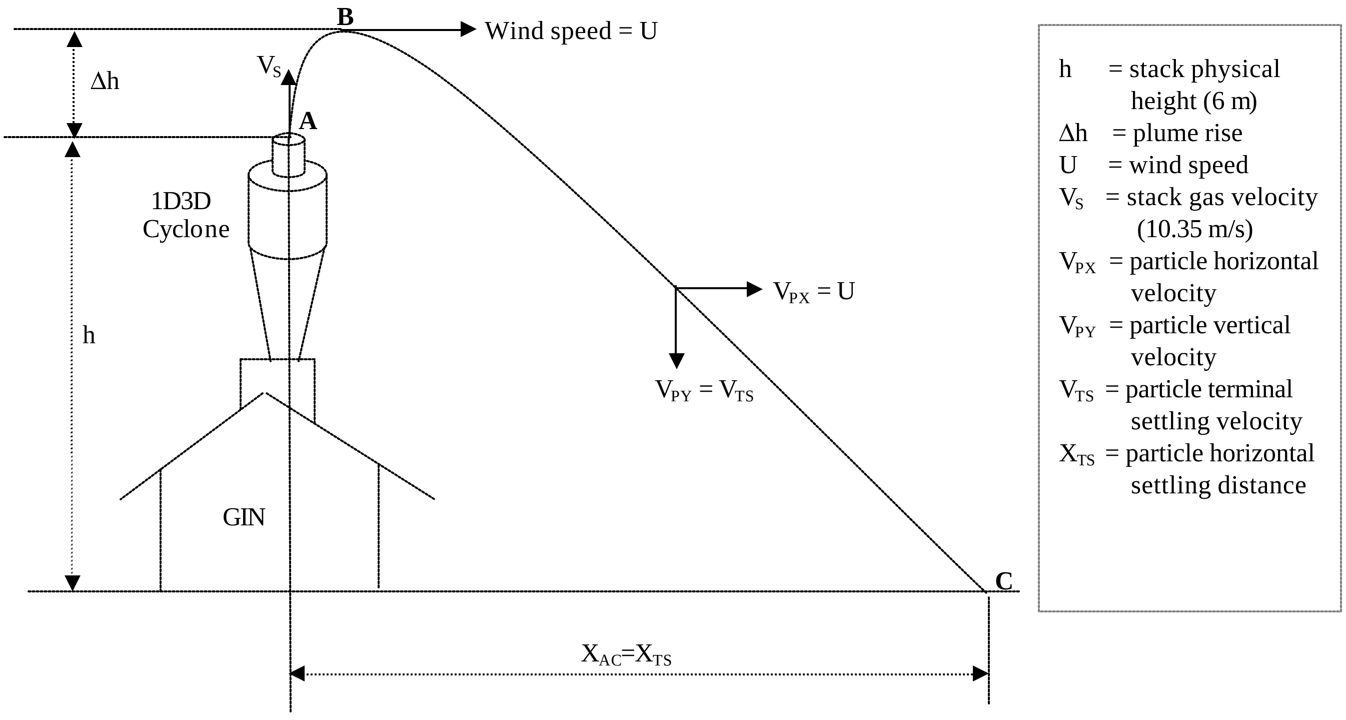

Figure 1. Diagram of particle settling trajectory

When a particle gets out of stack (A), it will travel with plume to the point (B) where particle vertical velocity $V_{py} = 0$. However, according to Hinds (1999), it only takes 0.1 seconds for a 100-µm particle to reach its terminal settling velocity and 1 ms for a 10-µm particle to reach its settling velocity. So it can be assumed that from B – C regime, particle velocity profile is:

$V_{px} = U$ (wind speed)

$V_{py} = V_{TS}$ (particle terminal settling velocity)

The assumption above indicates that in the B – C regime, there is no horizontal drag force on particle, and vertical drag force equals force of gravity. As a result, the following mathematical equations are obtained

$$\begin{cases} V_{px} = U \\ V_{py} = V_{TS} \end{cases} \longrightarrow \begin{cases} X = U*t \\ Y = V_{TS}*t \end{cases} \longrightarrow X = \frac{Y}{V_{TS}} * U \qquad (3)$$

In equation 3, when $Y = h+\Delta h$, $X = X_{BC}$ then

$$X_{BC} = \frac{h+\Delta h}{V_{TS}} * U \qquad (4)$$

Since $X_{AC} >> X_{AB}$, it is reasonable to assume that $X_{AC} \approx X_{BC}$. So, the particle terminal settling horizontal distance can be determined by the following equation

$$X_{TS} = X_{AC} = \frac{h+\Delta h}{V_{TS}} * U \qquad (5)$$

where

X_{TS} = particle horizontal settling distance (m),
h = stack physical height (6 m),
Δh = plume rise (m),
U = wind speed (m/s), and
V_{TS} = particle terminal settling velocity (m/s).

In equation 5, plume rise Δh is determined by the Holland formula (equation 6) and particle terminal settling velocity is determined by Stoke's Law (equation7)

$$\Delta h = 1.5 * \frac{V_S * d_S}{U} \qquad (6)$$

where

Δh = plume rise (m),
V_S = stack gas velocity (10.35 m/s),
d_S = stack inner diameter (cyclone outlet diameter = 0.457 m), and
U = wind speed at stack height (m/s)

$$V_{TS} = \frac{\rho_P * d_P^2 * g}{18\eta} = \frac{\rho_o * d_a^2 * g}{18\eta} \qquad (7)$$

where

V_{TS} = particle terminal settling velocity (m/s),
ρ_p = particle density (kg/m^3),
d_p = particle diameter (m),
g = acceleration of gravity (9.81 m/s^2),
η = air viscosity ($1.81*10^{-5}$ kg/m S)
ρ_o = the standard particle density (1000 kg/m^3), and
d_a = particle aerodynamic equivalent diameter (m).

The following steps describe an engineering analysis of PSD changes in the downwind plume. Thus, the change of PSD in the downwind plume at property line can be predicted through this process.

1. Use equations 5, 6 and 7 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

$$F_d = \frac{\int_0^{d} \frac{1}{\sqrt{2\pi} * d_p * \ln(GSD)} \exp\left[\frac{-\left(\ln d_p - \ln(MMD)\right)^2}{2\left(\ln(GSD)\right)^2}\right] dd_p}{\int_0^{d_{TS}} \frac{1}{\sqrt{2\pi} * d_p * \ln(GSD)} \exp\left[\frac{-\left(\ln d_p - \ln(MMD)\right)^2}{2\left(\ln(GSD)\right)^2}\right] dd_p} \qquad (8)$$

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 and 2 to obtain PSD in the downwind plume at distance X_2, X_3, ...

PSD's in the Downwind Plume

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 PSD's (MMD=10, 15, 20 and GSD=2), six wind speeds (0.5, 1, 2, 3, 4, 5, 6 m/s) are used as case study to predict PSD in the downwind plume at distances of 100m, 200m 300m, 400m, 500m and 600m. Tables 1-3 listed the summary of predicted PSD (MMD' and GSD') and mass fraction of PM_{10} in the downwind plume. The results in the tables 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, GSD and mass fraction of PM_{10} in the downwind plume.

Table 1. Predicted PSD's in downwind plume with source PSD of MMD = 10 µm, GSD=2

Wind speed (m/s)	Downwind 100 m			Downwind 200 m			Downwind 300 m		
	MMD (µm)	GSD	PM_{10}	MMD (µm)	GSD	PM_{10}	MMD (µm)	GSD	PM_{10}
0.5	9.9	2.00	50.28%	9.8	1.94	51.16%	9.6	1.92	52.22%
1	10.0	2.00	50.16%	9.9	1.97	50.70%	9.8	1.93	51.39%
2	10.0	2.00	50.07%	9.9	2.00	50.33%	9.9	1.96	50.70%
3	10.0	2.00	50.04%	9.9	2.00	50.19%	9.9	1.98	50.44%
4	10.0	2.00	50.02%	10.0	2.00	50.12%	9.9	2.00	50.28%
5	10.0	2.00	50.01%	10.0	2.00	50.08%	9.9	2.00	50.19%
6	10.0	2.00	50.01%	10.0	2.00	50.05%	10.0	2.00	50.13%

Wind speed (m/s)	Downwind 400 m			Downwind 500 m			Downwind 600 m		
	MMD (µm)	GSD	PM_{10}	MMD (µm)	GSD	PM_{10}	MMD (µm)	GSD	PM_{10}
0.5	9.4	1.84	53.69%	9.3	1.76	55.13%	9.1	1.74	56.50%
1	9.7	1.86	52.45%	9.5	1.83	53.32%	9.3	1.81	54.59%
2	9.8	1.92	51.27%	9.7	1.91	51.83%	9.7	1.86	52.45%
3	9.9	1.96	50.76%	9.8	1.94	51.16%	9.8	1.92	51.52%
4	9.9	1.97	50.51%	9.9	1.96	50.76%	9.9	1.92	51.07%
5	9.9	2.00	50.35%	9.9	1.97	50.55%	9.9	1.96	50.76%
6	9.9	2.00	50.26%	9.9	1.98	50.41%	9.9	1.97	50.60%

Table 2. Predicted PSD's in downwind plume with source PSD of MMD = 15 µm, GSD=2

Wind speed (m/s)	Downwind 100 m			Downwind 200 m			Downwind 300 m		
	MMD (µm)	GSD	PM_{10}	MMD (µm)	GSD	PM_{10}	MMD (µm)	GSD	PM_{10}
0.5	14.7	1.94	28.66%	14.0	1.81	30.31%	13.4	1.75	32.02%
1	14.8	1.96	28.39%	14.4	1.85	29.49%	13.8	1.80	30.69%
2	14.9	1.98	28.16%	14.7	1.90	28.75%	14.4	1.85	29.49%
3	15.0	1.99	28.06%	14.9	1.94	28.45%	14.6	1.90	28.98%
4	15.0	2.00	28.01%	14.9	1.95	28.28%	14.7	1.93	28.66%
5	15.0	2.00	27.98%	14.9	1.97	28.17%	14.8	1.95	28.45%
6	15.0	2.00	27.97%	14.9	1.99	28.11%	14.8	1.96	28.32%

Wind speed (m/s)	Downwind 400 m			Downwind 500 m			Downwind 600 m		
	MMD (µm)	GSD	PM_{10}	MMD (µm)	GSD	PM_{10}	MMD (µm)	GSD	PM_{10}
0.5	12.8	1.64	34.22%	12.3	1.59	36.30%	11.9	1.54	38.19%
1	13.4	1.69	32.37%	12.9	1.66	33.68%	12.4	1.61	35.52%
2	13.9	1.80	30.49%	13.6	1.75	31.41%	13.2	1.72	32.37%
3	14.4	1.84	29.60%	14.0	1.81	30.31%	13.8	1.78	30.91%
4	14.5	1.89	29.13%	14.3	1.86	29.60%	14.2	1.80	30.14%
5	14.7	1.90	28.81%	14.5	1.88	29.21%	14.3	1.85	29.60%
6	14.7	1.93	28.62%	14.6	1.90	28.92%	14.4	1.88	29.30%

Table 3. Predicted PSD's in downwind plume with source PSD of MMD = 20 µm, GSD=2

Wind speed (m/s)	Downwind 100 m			Downwind 200 m			Downwind 300 m		
	MMD (µm)	GSD	PM_{10}	MMD (µm)	GSD	PM_{10}	MMD (µm)	GSD	PM_{10}
0.5	19.0	1.84	16.92%	17.5	1.68	18.86%	16.3	1.58	20.74%
1	19.2	1.91	16.57%	18.2	1.73	17.92%	17.2	1.65	19.28%
2	19.6	1.93	16.25%	19.0	1.82	17.04%	18.2	1.73	17.92%
3	19.8	1.94	16.10%	19.4	1.86	16.64%	18.7	1.79	17.32%
4	19.9	1.96	16.02%	19.5	1.89	16.42%	19.0	1.84	16.92%
5	20.0	1.97	15.97%	19.7	1.92	16.27%	19.4	1.86	16.64%
6	20.0	1.98	15.95%	19.9	1.93	16.18%	19.5	1.89	16.48%

Wind speed (m/s)	Downwind 400 m			Downwind 500 m			Downwind 600 m		
	MMD (µm)	GSD	PM_{10}	MMD (µm)	GSD	PM_{10}	MMD (µm)	GSD	PM_{10}
0.5	15.2	1.51	23.12%	14.4	1.46	25.33%	13.7	1.43	27.36%
1	16.1	1.57	21.12%	15.4	1.53	22.54%	14.6	1.49	24.50%
2	17.4	1.65	19.06%	16.6	1.62	20.08%	16.1	1.58	21.12%
3	18.0	1.74	18.05%	17.5	1.67	18.86%	17.0	1.64	19.52%
4	18.5	1.78	17.49%	18.0	1.73	18.05%	17.6	1.74	18.67%
5	18.8	1.78	17.10%	18.4	1.78	17.59%	18.0	1.73	18.05%
6	19.0	1.85	16.87%	18.7	1.80	17.24%	18.3	1.76	17.69%

For source PSD of MMD=10µm and GSD=2, at wind speed of 0.5m/s, MMD changes from 10 µm to 9.1 µm, GSD changes from 2 to 1.74 at 600 m downwind, whereas, at wind speed of 6m/s, MMD changes from 10 µm to 9.9 µm, GSD changes from 2 to 1.97. The higher the wind speed, the smaller the change of MMD and GSD. Besides the change of MMD and GSD, mass fraction of PM_{10} also changes with change of wind speed and downwind distance. PM_{10} increases with increase of downwind distance (50.28% at 100 m vs. 56.50% at 600m when wind speed is 0.5 m/s). PM_{10} changes from 50% to 56.50% at 600 m and 0.5 m/s wind speed, whereas, at wind speed of 6 m/s, PM_{10} changes from 50% to 50.60% at 600 m downwind. The higher the wind speed, the smaller the change of PM_{10}.

Gravitational settling has greater impact on downwind PSD to those sources PSD with larger MMD's. At wind speed of 0.5 m/s and 600m downwind distance, MMD and GSD change from source of 10 µm and 2 to 9.1 µm and 1.74 versus change from source of 20 µm and GSD=2 to 13.7 µm and 1.43.

Figures 2-4 also show trend of changes in MMD and GSD in the downwind plume. For a given source PSD and wind speed (0.5m/s), the longer distance, the smaller is the MMD and GSD (sharper slope of cumulative PSD curve). Previous research at Texas A&M University suggested that PM_{10} sampler inherent sampling error is a function of PSD in the air. The larger MMD, the bigger sampling error will occur for a given GSD. From results of this research, it would be superficially concluded that particle settling mechanism could reduce PM_{10} sampler's inherent sampling error by placing the sampler at a distance that the larger particles have settled out. However, GSD has significant impact on PM_{10} sampling error as well. In fact, the smaller GSD will introduce bigger sampling error. PM_{10} sampler sampling error is more sensitive to GSD than to MMD. Further study will be conducted to address impact of changes of PSD in the downwind plume on PM_{10} sampler's sampling error problem.

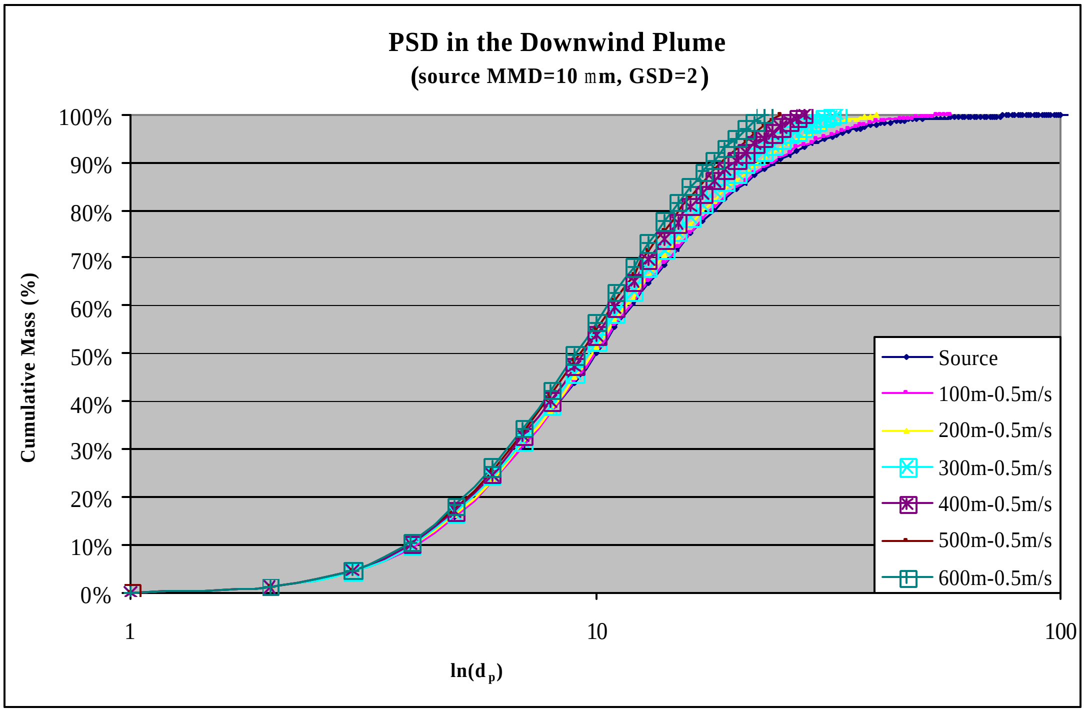

Figure 2. Predicted PSD's in downwind plume at wind speed of 0.5 m/s (source PSD of MMD = 10 µm, GSD=2)

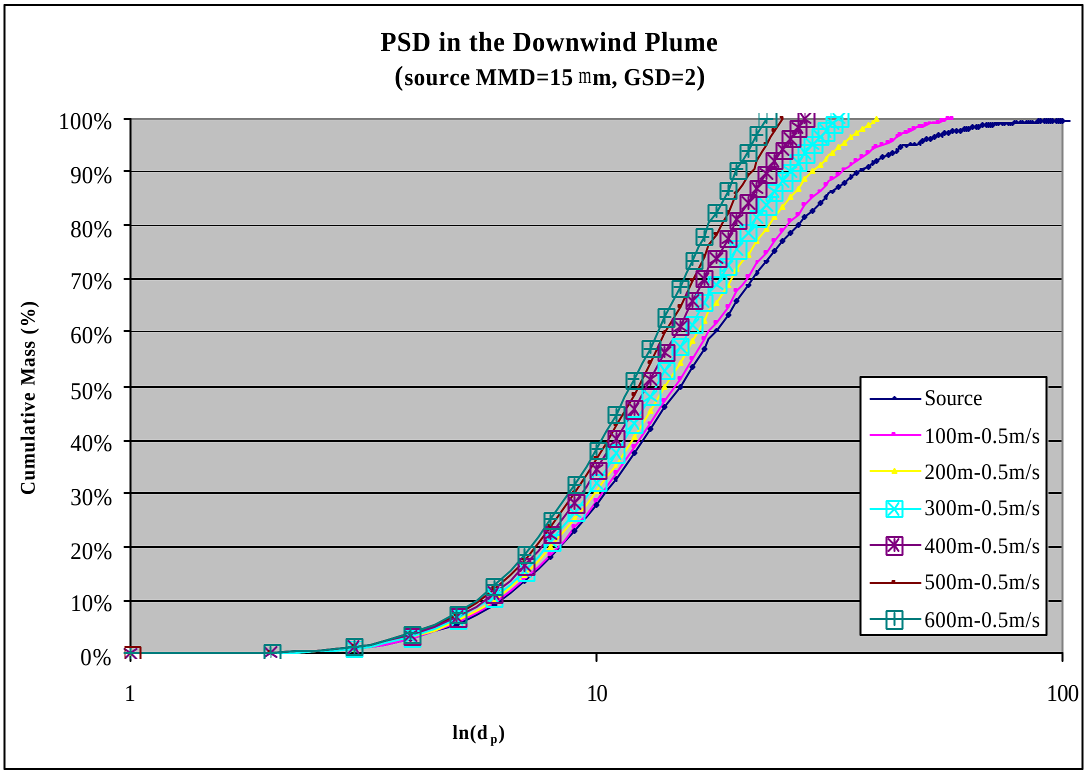

Figure 3. Predicted PSD's in downwind plume at wind speed of 0.5 m/s (source PSD of MMD = 15 µm, GSD=2)

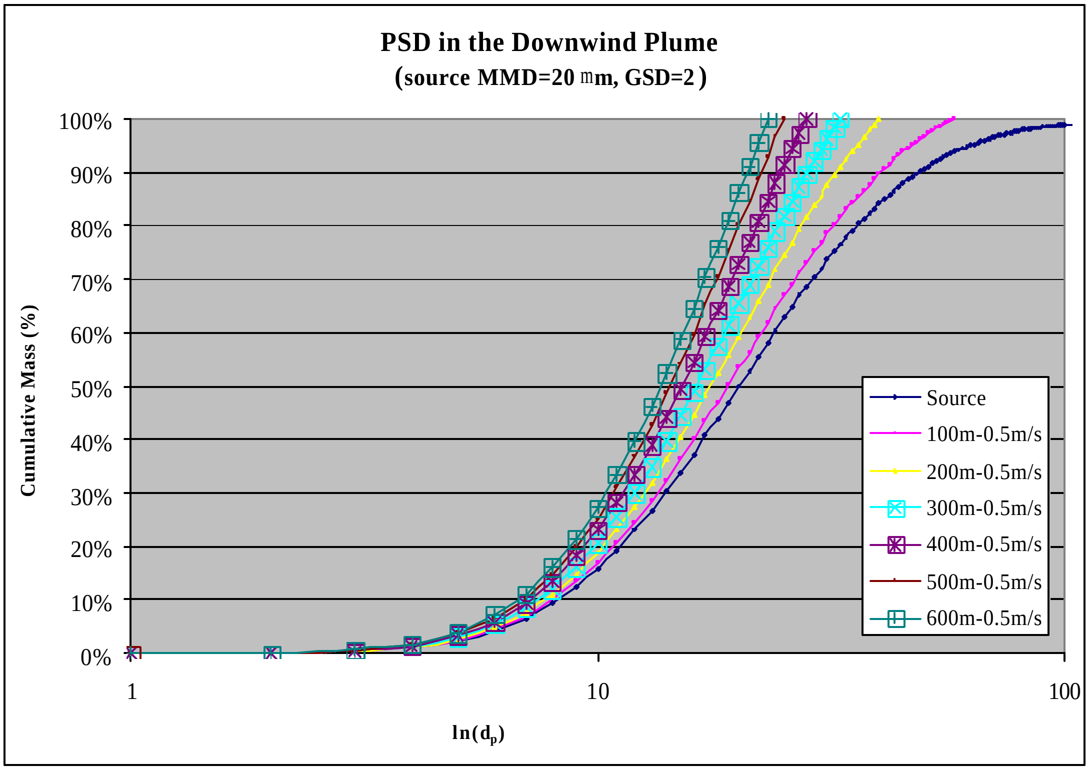

Figure 4. Predicted PSD's in downwind plume at wind speed of 0.5 m/s (source PSD of MMD = 20 µm, GSD=2)

Summary

An engineering approach to analyze PM dry deposition due to gravitational settling is summarized in this paper. Particle horizontal settling distance is determined based upon wind speed and particle terminal settling velocity. New PSD in the downwind plume is calculated based upon particle horizontal settling distance and source PSD. Results of this research indicate that change of PSD in the downwind plume is a function of wind speed, downwind distance and source PSD. Both MMD and GSD in the downwind plume decrease with increase of downwind distance and source MMD. At higher source MMD, there was a big change in MMD and GSD of dust in the downwind plume. There was also a big change in the MMD and GSD of dust in the downwind plume over longer downwind distances. However, the change of wind speed has inverse impact on the change of downwind PSD. MMD and GSD in the downwind plume decrease with decrease of wind speed. Gravitational settling causes significant change of MMD and GSD in the downwind plume and thus, has significant impact on the PM_{10} sampling error problems. Future research is needed to quantify this impact for more accurate PM_{10} measurement

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