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WIND TUNNEL TESTING PROTOCOL FOR EVALUATING AEROSOL SAMPLERS USING POLY-DISPERSED PARTICLES

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Abstract

Wind tunnel testing is required by USEPA for evaluating Particulate Matter samplers. In the past, most wind tunnel studies employed mono-dispersed aerosols as test particulate matter. Compared to the mono-dispersed aerosols, using poly-dispersed particles have two primary advantages: (1) better simulation of the performance of samplers in the real world and (2) significantly reduced experimental time and cost. A new wind tunnel testing protocol has been developed to use poly-dispersed particles. This paper will discuss dispersion of the test particulate matter, sampler/filter quality assurance, sample analysis, and data processing. The sampling protocol was employed to test sampler model BGI PQ100/200 PM_{10}. Initial results of sampler cut point and slope will be presented.

Introduction

Recently, the state and federal agencies are under increasing public pressure to regulate agricultural dusts (USEPA, 2004), which leads to an increasing need for accurate emission data for particulate matter. However, current particulate matter (PM) samplers, which work well for urban dusts, may be associated with a significant error for agricultural dusts due to the interaction of the aerosol Particle Size Distribution (PSD) and the sampler's performance characteristics (Buser, 2004). Therefore, determining the sampling error associated with PM samplers exposed to agricultural dust has become a top issue in agricultural air quality study.

Wind tunnel testing is likely the best approach to quantify the sampler's characteristics. The dust wind tunnel allows control of wind speeds and particulate matter concentration passing a given sampler inlet. Since the dust wind tunnel provides a cross sectional testing area with uniform velocity and concentration, isokinetic samplers can be used together with the aerosol samplers. Using the dust collected by isokinetic samplers as a reference, wind tunnel testing can generate the penetration curve for PM samplers from which, the cut point and slope can be obtained.

Past wind tunnel studies employed the monodispersed solid/liquid aerosol as the testing PM. There are two primary concerns associated with using monodispersed particles: (1) the experimental procedure associated with mono-dispersed aerosols is tedious, time-consuming and expensive; and (2) the mono-dispersed aerosols do not fully represent real world aerosols. Therefore, a new wind tunnel testing protocol is needed to allow testing with poly-dispersed dusts.

This study will first address the concerns associated with developing the testing protocol, and then introduce the wind tunnel testing protocol and the preliminary testing results of louvered dichotomous PM_{10} inlets. The louvered dichotomous PM_{10} inlet has been tested in several other wind tunnels (McFarland and Ortiz, 1984, VanOsdell and Chen, 1990, VanOsdell, 1991, Tolocka et al., 2001) using mono-dispersed solid and liquid particles as the test PM. Its performance has been very robust: the cut point and slope was found to be within 10 ± 0.5 µm and 1.5 ± 0.1 (Table 1). Therefore, its test results will provide data to compare with other methods using mono-dispersed PM.

Table 1. Performance of low-volume louvered dichotomous PM_{10} inlets.

Reference #	Testing Dust	Inlet Model	50% cutpoint (µm)		
			2 km/h	**8 km/h**	**24 km/h**
McFarland and Ortiz	monodispersed aerosol	SA 246B	9.9	10.2	10.0
VanOsdell and Chen	monodispersed aerosol	SA 246B	9.8	10.0	9.9
VanOsdell	monodispersed aerosol	R&P 10 µm inlet	9.82	-	9.58
Tolocka et al	monodispersed aerosol	Dichotomous	9.9	10.3	9.7

Methods

Development of Wind Tunnel Testing Protocol

USEPA's Requirements

The dust wind tunnel used to evaluate PM_{10} samplers must satisfy the performance requirements for the uniformity of the wind velocity and aerosol concentration as stated in Title V (USEPA, 1987): the maximum deviation of aerosol concentration and velocity from the mean must be less than 10% at the wind speeds of 2, 8, and 24 km/h. Recently, we designed and built a new dust wind tunnel facility and evaluated its performance. The air velocity of the wind tunnel can be varied from 2 km/h to 24 km/h. The velocity is uniform within 10% of the mean. A Generic Tee Plenum System (GTPS) (Han, 2003) was used to achieve good mixing of particles and to achieve uniform concentrations throughout the sampler test chamber. In the test section of the wind tunnel, the particle concentration and airflow velocity was uniform within 10% of the mean. This new wind tunnel satisfies USEPA's wind tunnel requirements for testing PM_{10} samplers. Details of this wind tunnel testing facility has been described elsewhere (Chen et al., 2006).

Dust Concentration and Agglomeration Consideration

The primary issue associated with feeding the test dust into the wind tunnel, is the ability to provide a wide range of dust feed rates to facilitate testing the sampler's performance under a wide range of PM concentrations. A key technical challenge associated with dispensing the dust was ensuring minimal agglomeration of the dusts in the test section. Small particles may stick to large particles because of electrostatic and surface forces. If agglomeration problem persists, it may significantly affect the accuracy of sampling efficiency estimation.

A low-cost, simple dust feeding system was fabricated (Figure 1). The fly ash -discharging feed rate was adjustable from 0.01 to 100 g/min by adjusting the exit hole size and the air flow to the hopper vibrator. During dust injection, any agglomerated dust will be broken up by the shear force created in the throat of the aspirator unit and at the ejection outlet. Examining the dusts collected in the testing chamber by Environmental SEM (Electroscan ESEM E-3), it was found that at all the three wind speed of 2, 8, 24 km/h, no agglomeration was found among particles with a volume diameter greater than 5 µm. At 2 and 8 km/h, approximately 10% of small particles with volume diameter smaller than 3 µm were found stuck to particles with volume diameters larger than 5 µm. This small percentage of agglomeration should not significantly change the aerodynamic diameter of the larger particles and should not significantly affect the sampler's ability to capture them.

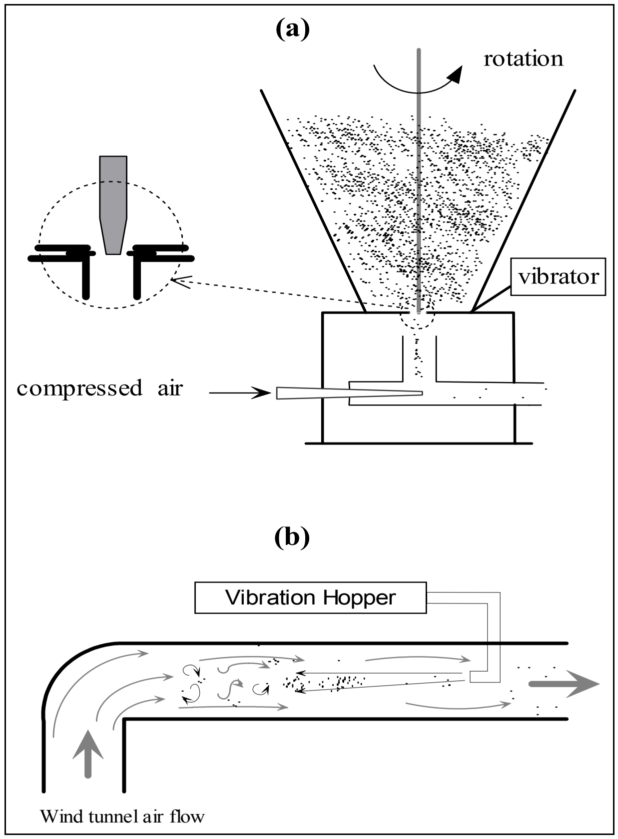

Figure 1. The sketch of the vibration-hopper dust-feeding system (a) outside of the wind tunnel (b) injection into the wind tunnel.

Ideal Isokinetic Sampler

A good reference sampler is critical to aerosol sampling investigation. Two types of isokinetic samplers were compared for use as a reference: a high-volume isokinetic sampler operating at 800 L/min and a low-volume isokinetic sampler operating at approximately 11 L/min. The sampling flow rate of the high-volume isokinetic sampler was adjusted manually by a valve and flow rate was determined by measuring the pressure drop across the calibrated orifice meter. For the low volume isokinetic sampler, a mass flow controller (Module: FMA542ST-24VDC, Omega Inc, USA) was used to control the sampling flow rate. A velocity transducer (Module 8455, TSI Inc, USA) was installed in a flexible arm so that it could be positioned upstream of the isokinetic sampler to monitor the wind velocity entering the isokinetic probe. Another set of sensors for static pressure (Model ASCX15AN, Honeywell, Inc.), temperature and relative humility (Module HX94V, Omega Inc, USA) were installed just downstream of the test section. The mass flow controller and all the sensors were connected to a real time field controller (National Instrument Inc. USA). A LabView™ program was developed to control the mass flow rate so that the velocity entering the probe was adjusted automatically to match the free-stream velocity approaching the inlet.

For both isokinetic samplers, the dust loss to the inner surface was recovered to another Teflon filter using a micro-vacuum sampler. The collected dust on the "inlet loss" filter and "sampling" filter were dispensed into the same electrolyte solution for the coulter counter analysis to get a reference PSD of the dust in the air. Six experiments were carried out for the wind speed of 8 km/h. The low-volume isokinetic sampler measured aerosol concentrations were found to be within the 10% of the high-volume isokinetic sampler. The low-volume isokinetic sampler measured particle size distribution was found to be almost the same as the high-volume isokinetic sampler.
Therefore, it was concluded that the two isokinetic samplers had comparable performance characteristics.

Only the low volume ideal isokinetic sampler will be used in the future as the reference sampler for the following reasons: (1) The low-volume isokinetic sampler operates at flow similar to the test samplers. (2)Using high-volume isokinetic samplers requires use of larger filters than is used for the low-volume samplers. The larger filter requires use of a different protocol for gravimetric analysis and for dispersion of particles in the Coulter Counter™ analysis process.

Dust Recovery

To get a good reference of dust concentration from the ideal isokinetic sampler, dust deposited on the inner surface of the isokinetic probe was recovered using the micro-vacuum sampling technique. The dust recovered by the micro-vacuum deposited onto a 47 mm filter. During the vacuuming process, some dust was lost to the inner surface of the nozzle of the micro-vacuum sampler. To recover this dust, a small brush was developed to reach inside the nozzle and break the dust loose while the vacuum pump was operating. Before each test, the inner walls of samplers were cleaned thoroughly with ethanol. After each test, the probes were handled carefully to prevent the dislocation of deposited dust. Before vacuuming, the working area and the outer surface of the reference probe were wiped clean using a damp paper towel.

Other Considerations

To select dust to be used as a poly-dispersed test dust, several factors were considered such as the cost, safety and physical properties of the dust. For our large wind tunnel, large amount of dusts will be used, which limits our choices to relatively inexpensive dusts. Corn starch may be a good candidate since it is spherical in shape and has a PSD similar to many applications. However, it must be used carefully to avoid conditions were an explosion could occur. Coarse Arizona road dust was selected for this study because of four reasons: (1) it is non-explosive; (2) it is relatively cheap compared to other manufactured testing dusts such as glass beads; (3) it has a large fraction of large particles so that the dust reaching the test area will have a MMD near 10 microns; (4) its physical properties are similar to some agricultural dusts.

Electrostatic effect is another factor that may influence the performance of PM samplers. During the dust feeding process, particle-to-particle and particle-to-wall contact can result in electrostatically charged particles. To minimize the electrostatic effect on sampler performance, the dust feeding system and the sampling system were electrically connected to ground.

Wind Tunnel Testing Protocol

The wind tunnel testing protocol consists of: (1) pre-experimental preparation; (2) wind tunnel testing; (3) deposited dust recovery; (4) particle size analysis; and (5) post-experiment data analysis.

Step 1: Pre-experiment Preparation

For all experiments, 47 mm Teflon filters were used. The filter was weighed on a microbalance (Mettler M3) that has a precision of 0.01 mg after charge neutralization. Before running each test, the sampling systems for the isokinetic reference probe and the sampler inlet being tested were checked for gas leaks and the inner and outer surface of each inlet, the testing inlets and isokinetic reference probe were carefully cleaned using paper towels dampened with ethanol. The flow rate of the sampler inlet being tested was measured with an orifice meter. The orifice meter was calibrated every six months. Pressure transducers used to measure the pressure difference across the orifice plate were calibrated every six months. Before each run, the zero point of the pressure transducers was checked. Some dust deposits in the wind tunnel during each test. If this dust is re-suspended, it may introduce some error into the experiment. Therefore, before each run, the fan was operated at its maximum speed to clean the deposited dust out of the wind tunnel.

Step 2-4: Wind tunnel testing, dust recovery; particle size analysis

Wind tunnel testing is primarily a means to expose the sampler inlet being evaluated and the isokinetic reference sampler simultaneously to the aerosol stream in the test section of the wind tunnel. The samplers inlets were located in the same horizontal plant to reduce the error that may be caused by vertical variation of the particle size distribution, though no spatial variability was fund in preliminary evalution of the wind tunnel. For each run, several steps were performed in the following order: adjust wind speed to desired condition, activate the computer program to control sampler flow rate, begin dust feeding, begin sampling, stop the fan and dust feeding, stop sampling, stop the computer program.

The dust deposited inside the probe of the isokinetic sampler was recovered using the vacuum technique as described above. The particle size distribution of the collected aerosols were analyzed using a Coulter Multisizer (Multisizer™ 3, Beckman Coulter, Inc. Fullerton, USA). The coulter analyses were then performed with a 100 µm aperture. The Coulter Counter Multisizer 3 calibrated by the manufacturer annually and by laboratory technicians every 100 runs. The electrolyte solution used is composed of 5% mass of lithium chloride in methanol.

Step 5: Data analysis
The diameter reported by the Coulter Counter ™ analysis was the volumetric diameter (d_e). Aerodynamic equivalent diameter (d_{ae}) is defined as the diameter of the spherical particle with a density of 1000 kg/m^3 that has the same settling velocity as the particle of interest (Hinds, 1999). Neglecting the Cunningham slip correction factor, the aerodynamic diameter can be converted from volumetric diameter to aerodynamic equivalent diameter by equation 1.

$$d_{ae} = d_e \left(\frac{\rho_p}{\chi \times \rho_o} \right)^{1/2} \quad (1)$$

Where χ is the shape factor and ρ_p is the particle density. For coarse Arizona road dust, the manufacturer-recommended specific gravity is 2.65. Its shape factor is 1.3 - 1.5. In this study, a shape factor of 1.4 was used. Reference concentration ($C_{reference}$) was defined as the concentration of dust in the air. It was the sum of aerosol concentration collected with isokinetic inlet (C_{iso}) and the concentration from isokinetic inlet vacuum ($C_{iso,vacuum}$). Overall sampling efficiency ($E_{PM10,sampling}$) was defined as the ratio of dust concentration in the final stage of the PM10 sampler, to the reference concentration:

$$E_{PM10,sampling} = C_{samp} / C_{reference} \quad (2)$$

where C_{samp} was the aerosol concentration collected with the testing sampler.

Results

Table 2, Experimental plan and results for wind tunnel tests of BGI PQ100/200 inlets.

Wind speed (km/h)	Referenc e probe (mm)	Dust concentration (µg/L)	Replicate s	d_{50} (µm)	slope	Referenc e MMD	Referenc e GSD
2	19.8	16.5	3	9.9	1.4	9.49	2.1
8	10.2	25	2	9.7	1.6	10.1	2.3
24	7.4	13	2	9.6	1.45	12.64	1.9

All the wind tunnel experiments that have been done were listed in Table 2. As can be seen from Table 2, for all three wind speeds, the cut points and slopes all satisfied USEPA's performance requirement for PM_{10} samplers: the cut point should be within 10 ± 0.5 µm and the slope 1.5 ± 0.1. The standard deviation of sampling efficiency was less than 5% among three runs at 2 km/h. Comparing the study using poly-dispersed aerosols with the study using mono-dispersed aerosols (Table 1), there is no significant different in the results. As in the studies cited that evaluated this sampler inlet with monodispered PM, this study found no statistical relationship between wind speed and the cut point. An example of the sampling efficiency curve is shown in Figure 2.

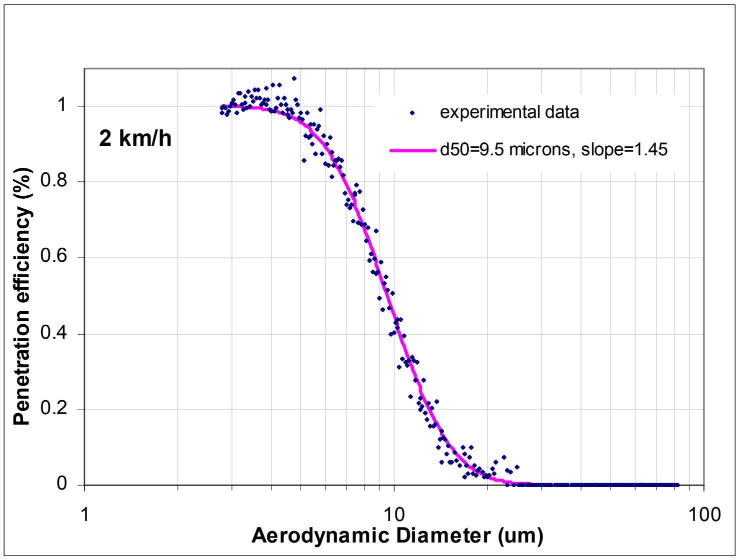

Figure 2. Wind tunnel test results for the BGI PQ100/200 PM_{10} inlet at 2 km/h.

Conclusions

This study developed a testing protocol for use of poly-dispersed dusts in order to investigate the performance of particulate matter samplers operating downwind of sources of coarse PM. The protocol provides a means to expose the sampler inlet being evaluated and the isokinetic reference sampler simultaneously to a consistent aerosol stream in the test section of the wind tunnel to provide a basis to evaluate the performance of the inlet being tested. Several primary issues were discussed in order to develop the testing protocol:

(1) The dust wind tunnel should have a uniform velocity profile and aerosol cloud in the test section.
(2) The dust feeding system should provide a wide range of feed rates and minimize dust agglomeration.
(3) The design and operation of isokinetic samplers for use as a reference.
(4) How to recover the dust lost to the inner surface of sampler inlets.
(5) How to select appropriate test dusts and avoid the effect of electrostatic charges on sampler's performance

The performance of the wind tunnel facility and sampler testing protocol have been evaluated by testing a louvered dichotomous PM10 sampler. The sampler's performance characteristics determined in this study were similar to those found in previous studies using monodispersed solid/liquid dust. The wind tunnel facility will now be used to evaluate PM sampler inlet performance when exposed to aerosols with much larger particles representative of agricultural operations.

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