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# A Dust Wind Tunnel for Particulate Matter Sampling Studies

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***Abstract.*** *A new wind tunnel has been designed, fabricated and evaluated for the study of particulate matter (PM) samplers. The air velocity of the wind tunnel ranges from 2 km/h to 24 km/h. The velocity is uniform within 10% of the mean. A new, low cost dust feeder system was designed, which is able to disperse dust into the wind tunnel over a wide range of concentrations (0.01 g/min–100 g/min). A Generic Tee Plenum System (GTPS) was used to achieve good mixing of particles in order to achieve uniform concentrations throughout the sampler test chamber. In the testing section of the wind tunnel, the particle concentration is uniform within 10% of the mean. In addition, a dust-loss collector was designed to recover >90% of the dust loss to the inner wall of sampler's inlet. This new wind tunnel satisfies USEPA's wind tunnel requirements for testing* $PM_{10}$ *samplers.*

**Keywords.** Dust wind tunnel, uniformity of particle cloud, uniformity of wind speed, dust feeder, dust-loss collector

## Introduction

A dust wind tunnel is designed to achieve uniform particle concentrations and wind speeds of magnitudes similar to those observed in typical ambient conditions. A properly-designed wind tunnel can provide well controlled experimental conditions for aerosol sampling investigations (Ranade et al., 1990, Witschger et al., 1997). Wind tunnels have been used to explore sampling theory by isolating and controlling variables that may effect sampler performance such as PM concentration, wind speed and orientation (Lai and Chen, 2000, Paik and Vincent, 2002, Paik and Vincent, 2004) and turbulence level (Hall and Emmott, 1994, Wiener et al., 1988). Wind tunnels have also been used to evaluate candidate samplers (Hall et al., 1994, McFarland et al., 1984, Ranade et al., 1990, Tolocka et al., 2001, Wagner and Leith, 2001, Wedding et al., 1985). Wind tunnels used to evaluate $PM_{10}$ or $PM_{2.5}$ samplers must satisfy the performance requirements for wind velocity uniformity and aerosol concentration uniformity as stated in Title V of the Clean Air Act Amendments of 1987 (USEPA, 1987). The requirements for wind tunnel performance at the sampler testing area specified by United States Environmental Protection Agency (USEPA) for testing ambient samplers are summarized in Table 1.

Table 1. USEPA requirements for the performance of wind tunnels for evaluating $PM_{10}$ and $PM_{2.5}$ samplers (USEPA, 1987).

| **Parameter** | | **$PM_{10}$ Requirement** | **$PM_{2.5}$ Requirement** |
|---|---|---|---|
| Air Velocity | *Uniformity* | ±10% for 2, 8 and 24 km/h | ±10% for 2 and 24 km/h |
| | *Measurement* | 1) Minimum of 12 test points<br>2) Monitoring techniques: precision ≤ 2% ; accuracy ≤ 5% | |
| Aerosol Concentration | *Uniformity* | ±10% of the mean. | ±5% of the mean |
| | *Measurement* | No less than 5 evenly spaced isokinetic samplers<br>The sampling zone shall have a horizontal dimension not less than 1.2 times the width of the test sampler at its inlet opening and a vertical dimension not less than 25 centimeters | |
| Particle size | *Measurement* | Accuracy ≤ 0.15 µm; size resolution ≤ 0.1 µm | |

The USEPA wind tunnel (Ranade et al., 1990) and most other wind tunnels used in the evaluation of sampler performance used monodisperse liquid or solid aerosols to determine the effectiveness of PM samplers for aerosols of a certain size. A recent study (Buser, 2004) revealed that the concentration measured by PM samplers may not represent the “true” PM concentration due to the interaction of the particle size distribution (PSD) and sampler characteristics. Theoretical analyses indicated that the interaction of the PSD and the $PM_{10}$ sampler performance may result in over sampling biases of $PM_{10}$ concentrations as high as 200% for large particles such as those commonly found in agricultural industries.

Poly-disperse aerosols will be used as the main testing material in our study to verify Buser’s theory. The following paper will first introduce the structure and the components of the wind tunnel and then describe the experiments used to characterize the profile of the airflow velocity, the trace gas concentration, the dust concentration and the particle size distribution (PSD).

## Description of Wind Tunnel

The wind tunnel is constructed of plywood, and the inner wall of the tunnel is coated with acrylic latex paint for good sealing and a smooth finish. The fan is located in the first floor to reduce the effects of vibration; all the other parts of the wind tunnel are positioned on an elevated platform. Figure 1 shows the layout of the wind tunnel from an overhead view.

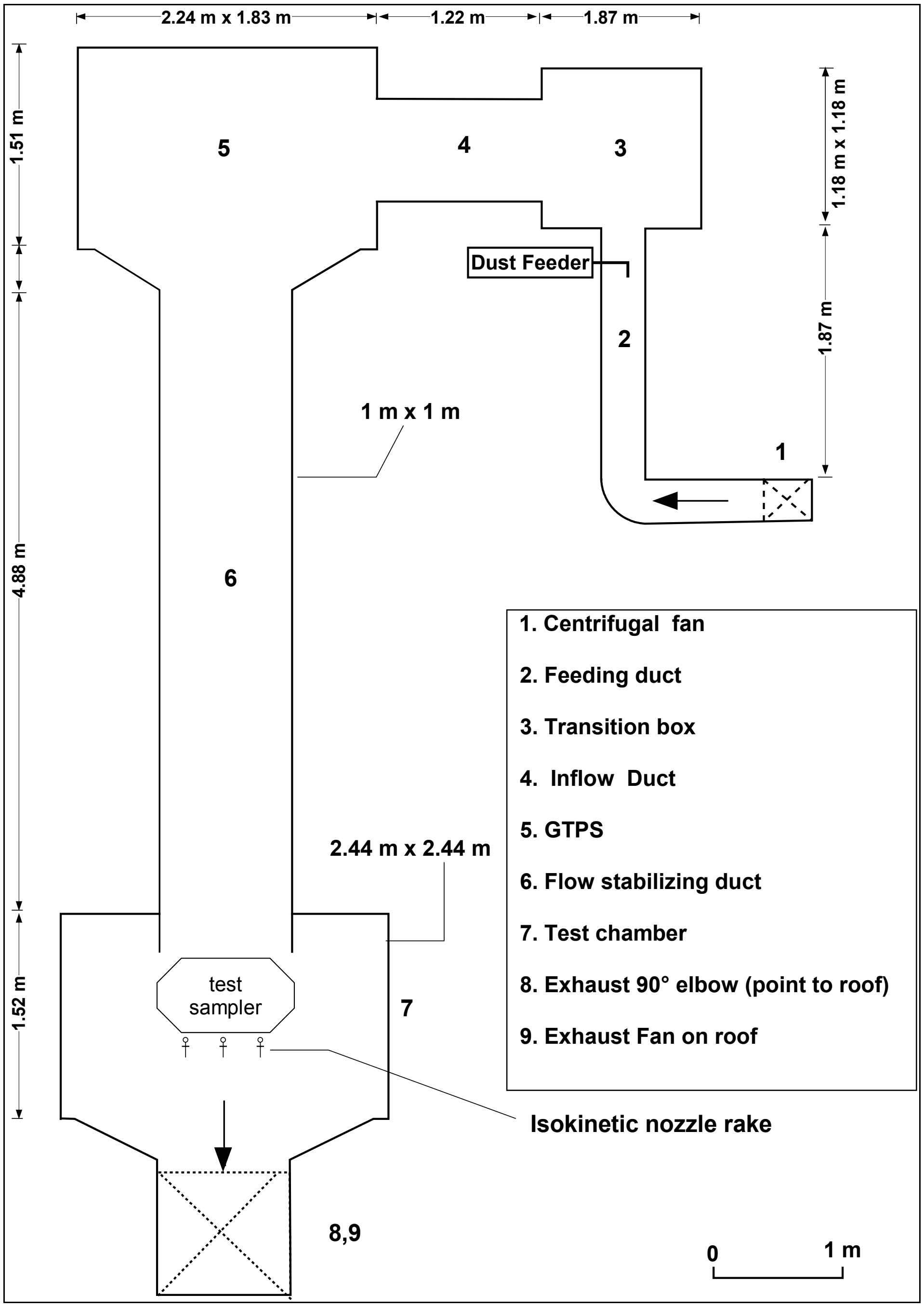


Figure 1. Wind tunnel schematic.

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 fan blows the air upward through a vertical transmission duct that matches the dimensions of feeding duct (2). The dust feeding system is located within the feeding duct. The transition box (3) functions as an elbow and a first stage-mixing chamber. Following the inflow duct is the GTPS mixing box (5). The air coming out of the GTPS passes through the flow-stabilizing duct (6) where the flow is stabilized. At the end of the stabilizing duct is the test chamber (7), which has an expanded cross sectional area to avoid wall effects and to make the best use of the testing area. Air coming out of the test chamber passes through a 90° exhaust elbow (8) which directs the flow out of the building through an exhaust fan on the roof (9).

The wind tunnel was constructed by bolting together modules that are each supported by a frame with wheels. In order to handle the high pressure in the wind tunnel, the modules used 2 cm thick wood panels and were reinforced with external studs.

### *Dust Feeder System*

Several dust feeders, built on different mechanism, were considered for used in these tests such as Wright, Turntable and Fluidized Bed. However, these commercially available dust feeders were either unable to provide the wide range of feeding rates required in this study or they were too expensive. Therefore, a low-cost, simple dust feeder system was developed in house. The dust feeder system is composed of two parts: a vibration hopper and a dust injector (Figure 2). The dust feed rate is controlled by the size of the hopper orifice and the flow rate of compressed air through the hopper vibrator. A rod mixer is used to break up dust cakes that may inhibit flow of dust. Compressed air is used to convey the particles into the wind tunnel.

Using fly ash obtained from a local power plant in Bryan, Texas, the linear feeding rate was verified. Adjusting the hole size and the air flow to the hopper vibrator, the feed rate is adjustable from 0.01 to 100 g/min. For the same material and the same conditions, the coefficient of variance (COV) of the feeding rates among replicated experiments was less than 15%, indicating a reasonable repeatability of the feeding rate.

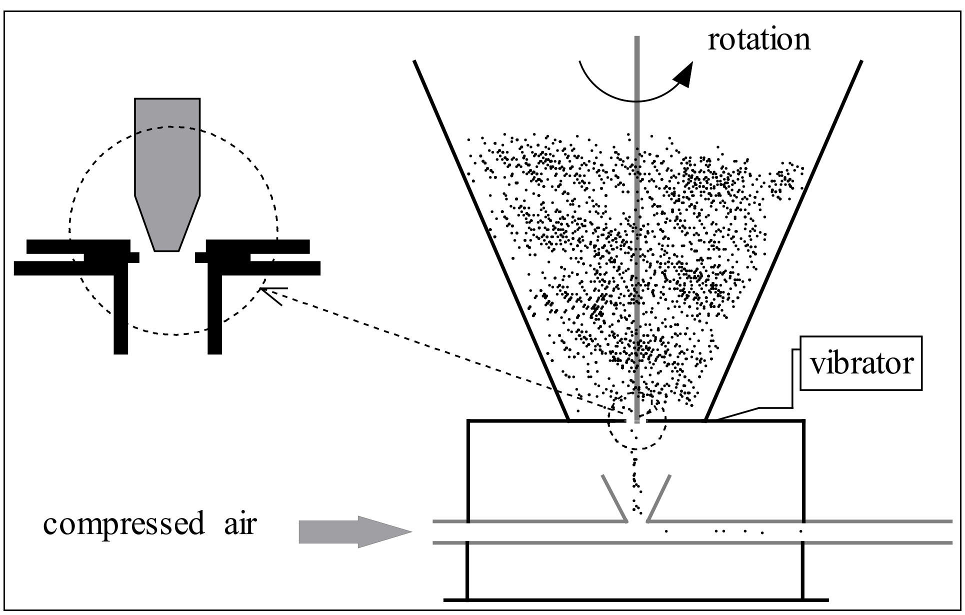


Figure 2. Dust feeding system.

### *Mixing System*

Unlike aerodynamic wind tunnels, dust wind tunnels used in ambient or personal sampler investigations simulate the aerosol concentration and wind speed in the surface layer of the troposphere rather than in the stratosphere. Therefore, for dust wind tunnels, achieving the uniformity of dust cloud is more important than achieving the low turbulence. To obtain the high turbulence required for dust mixing, wind tunnels can either take advantage of the high turbulence area in the tunnel or use devices designed to create the needed the turbulence. The techniques and devices used in the past include a counter mixing fan (Ranade et al., 1990), an air blender (Witschger et al., 1997) and a multiple point feeding system (Heist et al., 2003). The ideal mixing mechanism should minimize pressure and particle loss.

In this wind tunnel, a Generic Tee Plenum Systems (GTPS) was used as the static air mixer. GTPS are rectangular boxes with square or round inlets. One type of GTPS is shown in Figure 3. GTPS were developed and evaluated by the Aerosol Technology Laboratory at Texas A&M University (Han, 2003, McFarland et al., 1999). It was found that GTPS have the advantage of mixing thoroughly at a low-pressure drop. The COV of the gas concentration will reach 5% at 6.5 diameters downstream of the GTPS. Muffle

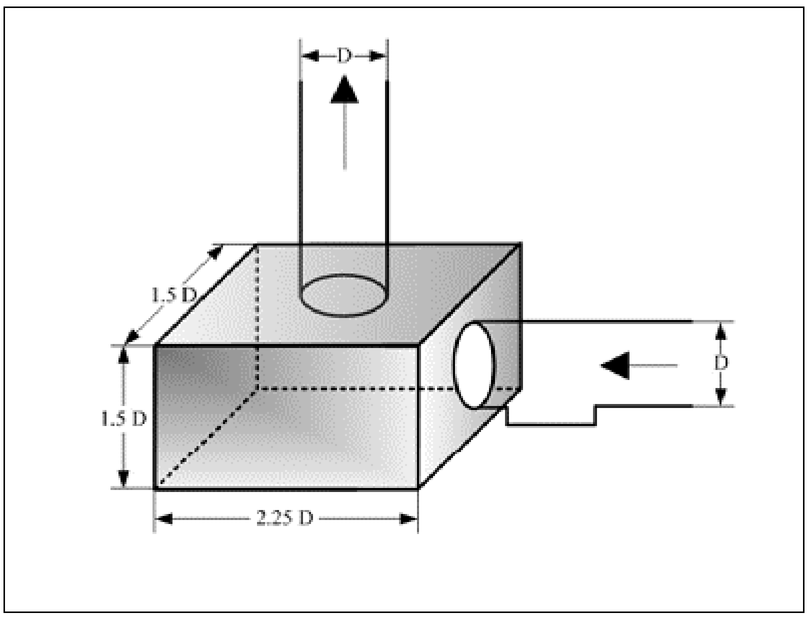


Figure 3. Characteristic dimension of small horizontal generic tee plenum system (Han, 2003)

### *Dust-Loss Collector*

To get a good reference of dust concentration from the ideal isokinetic sampler and to obtain the aspiration efficiency of PM samplers, dust deposited on the inner surface of the samplers should be recovered. A dust-loss collector was designed to serve this purpose. The dust-loss collector was made from a 47mm filter holder. 6.4 mm diameter tubing was added to the opening of filter holder to increase the sampling flow velocity. The size of the tip of the tubing was reduced so that it can reach small corners. Figure 4 shows the inlet of the dust-loss collector. To use this unit, the outlet of the filter holder was connected to a pump and the deposited dust on the surface of samplers was vacuumed and collected onto a Teflon filter. During vacuuming, some dust will be lost to the inner surface of this dust-loss collector. To recover this portion of dust loss, a small brush was designed (Figure 5) to clean the inner surface of the dust collector. This dust will be collected on the filter by brushing while the vacuum pump is operating.

Figure 4. The dust-loss collector.

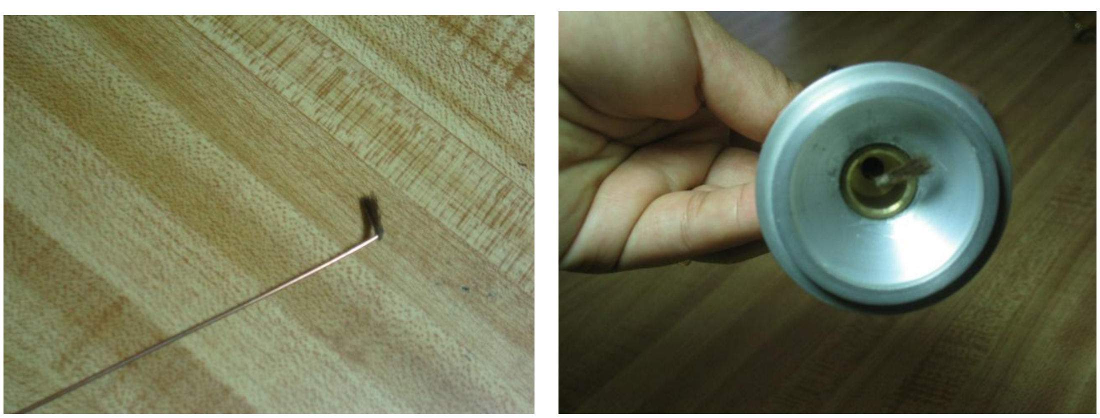

Figure 5. The brush for the dust loss collector.

To measure the recovering efficiency of the dust collector, a known mass of fly ash was sucked into the dust collector. A recovery rate of >90% was found in all experiments indicating that this technique can be useful for recovering the dust loss in future aerosol studies. The sampling flow rate for the dust loss collector was ~ 2.8 $m^3$/h.

## Performance Assessment

### *Velocity and Turbulence Profile*

Velocity and turbulence in the sampler test area of the tunnel were measured using a hot wire anemometer (Model 8386, TSI Inc., Shoreview, MN) with a precision of 0.1 m/s and accuracy of +1.5 %. Velocity readings were recorded every 2 second for one hour at a fixed point. From this data, it was found that 3-minute averaged velocity and 10-minute turbulence intensity can be used as the representative velocity and turbulence intensity since their values were within ±2% of the one-hour averaged velocity and turbulence intensity.

To obtain the velocity profile, the cross sectional area used for sampling was divided evenly into 16 grids, and the velocity was measured at the center of each grid. For each grid, thirty or more continuous readings were recorded within 3 minutes. Duplicate sets of measurements were made for each wind speed. The velocity profiles were determined at two different cross-sectional areas: one directly after the flow stabilizing duct and the other in the middle of the test chamber. For both cross-sectional areas, the gradient of velocity was measured to be < 7 % and the COV for the cross sectional area was < 3% (Table 2), satisfying the USEPA's performance requirement for dust wind tunnels. Furthermore, it was found that the maximum and minimum velocity at the two cross sectional areas was well within 10% of the averaged velocity of either cross sectional area.

Table 2. The uiformity of wind velocity.

| Wind speed | | COV | Deviation from mean | |
|---|---|---|---|---|
| | | | maximum | minimum |
| 2 km/h | Directly after flow stabilizing duct | 2.1% | 1.03 | 0.97 |
| 8 km/h | | 2.6% | 1.05 | 0.97 |
| 24 km/h | | 1.9% | 1.03 | 0.97 |
| 2 km/h | Middle of test chamber | 2.1% | 1.04 | 0.98 |
| 8 km/h | | 1.4% | 1.03 | 0.98 |
| 24 km/h | | 1.4% | 1.03 | 0.98 |

The reproducibility of the velocity profile was assessed by carrying out multiple replicated experiments for the same wind speed. For each data set, the mean of the whole cross sectional area was obtained by averaging the velocities at several locations. The ratio of each velocity to the mean is an indication of the relative velocity level of the specific location compared to the whole cross sectional area. The inter-experiment variance of the non-dimensional ratio evaluates the reproducibility of the relative velocity level. A low COV (<2% over 4 experiments at ~21 km/h for 9 evenly distributed points) showed that the wind tunnel maintains a repeatable velocity profile.

Although there is no requirement for the turbulence level in the USEPA's standards, the turbulence was measured. The turbulence for each wind velocity was measured at the center of cross sectional area for more than 10 minutes. Turbulence intensity was found to decrease with the increasing wind speed in the wind tunnel (Figure 6). Turbulence intensities were measured to be 10%, 7.5% and 5% for the airflow velocity of 2, 8 and 24 km/h, respectively.

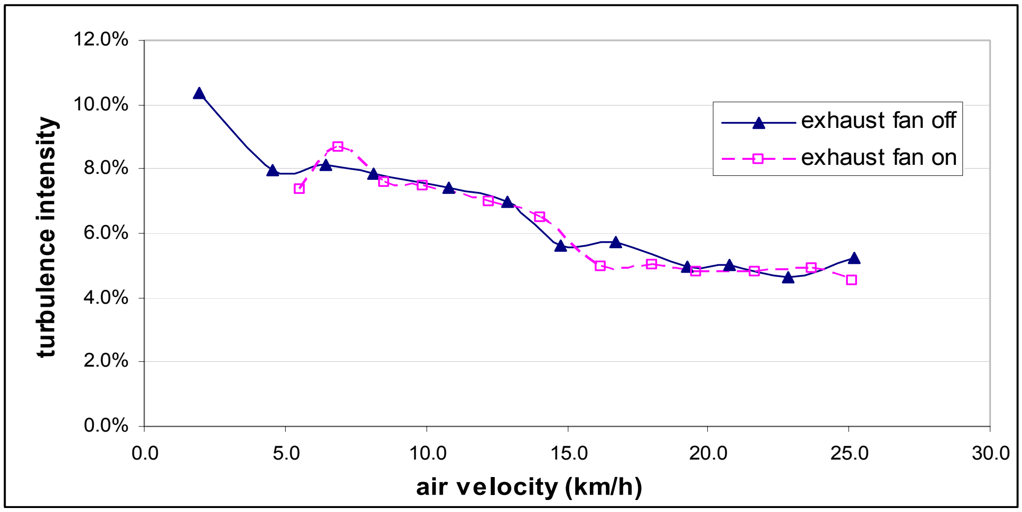


Figure 6. Turbulence intensity versus air flow velocities.

### ***Trace Gas Profile***

Sulphur hexafluoride ($SF_6$) was released into the main air stream from different locations in order to determine the mixing efficiency. Trace gas concentrations were measured directly downwind of the flow-stabilizing duct. The cross sectional area for testing was evenly divided into 9 equal areas. Air samples were extracted with 60 mL hypodermic syringes at the center point of each grid. The $SF_6$ concentration was measured using an electron capture gas chromatograph tracer gas monitor (AUTOTRAC Model 101, Lagus Applied Technology, San Diego, CA) which has a precision of ±4%. Multiple sets of samples were collected for each wind speed. The average of the COVs from multi-replicated experimental data sets was used as the representative COV for each experimental condition (Table 3).

Table 3. Trace gas concentrations uniformity.

| Wind speed | Releasing location | COV | Deviation from mean | |
|---|---|---|---|---|
| | | | maximum | minimum |
| 2 km/h | feeding duct | 2.3% | 1.06 | 0.96 |
| 8 km/h | | 1.5% | 1.03 | 0.97 |
| 24 km/h | | 1.2% | 1.02 | 0.98 |
| 2 km/h | center of GTP | 20.1% | 1.45 | 0.67 |
| 8 km/h | | 17.3% | 1.28 | 0.62 |
| 24 km/h | | 14.4% | 1.25 | 0.74 |
| 6 km/h | downstream of GTP | 133.5% | 4.06 | 0.01 |
| 20 km/h | | 75.6% | 2.83 | 0.29 |

When the gas was released in the feeding duct, upstream of the transition box, the COVs in the sampler test chamber were all less than 3%. When the gas was released in the feeding duct, upstream of GTPS, the COVs were in the range of 4-7%. When the trace gas was released downstream of the GTPS box. The concentration profile was found to have a COV of 134 % and a maximum deviation of 406% from the mean, indicating that the effective mixing came from the

GTPS and the transition box. Among all the experiments with the exception of release downstream of the GTPS, the deviation of trace gas concentration from the mean were all less than 10%. The reason why the mixing was better when the gas was released upstream of the transition box was that the transition box acted as another GTPS mixing box, thus enhancing the mixing. Therefore, for subsequent experiments, the dust was released in the feeding duct.

### *Concentration Profile of Dust Cloud*

The concentration uniformity of PM is a very important characteristic for wind tunnel design. To determine the concentration profile, both gravimetric and real time measurements were used. For the gravimetric method, a rack of nine isokinetic samplers was positioned in the test cross sectional area. The sampler holder stand was designed to be downstream of the samplers to reduce measurement interference. The total area of blockage of the isokinetic sampler composes only 2.7 % of the total area. The probes used for isokinetic samplers were machined conically from aluminum to hold 47 mm diameter filter holders. The design of the probe satisfies the requirement of Belyaev and Levin (1974) for the opening angle and the thickness of the edges. The inner surface of the nozzle was polished to reduce particle loss. Before the gravimetric experiment, clean 47 mm glass fiber filters were pre-weighed and all the probes were cleaned. Test duration varied from 5 to 40 minutes to achieve a loading of approximately 8 mg in each sampling filter. Either fly ash or Arizona Road Dust (ARD) was used for the tests. The dust lost to the inner surface of the ideal Isokinetic sampler was recovered to the Teflon filter of the dust loss collector by vacuuming. The two filters from the ideal Isokinetic sampler and the dust-loss collector were post-weighed. The dust concentration was calculated from the total weight of the dust on two filters. Multi-replicate experiments were run for the wind speeds of 2 km/h, 8 km/h and 24 km/h. For the three wind speeds, the COVs of dust concentration in the center of nine equal areas across the cross sectional area were less than 6%, and the average deviation from the mean was less than 10% (Table 4), satisfying the USEPA's performance requirement of the dust wind tunnels.

Table 4. Concentration uniformity of fly ash.

| Wind speed | Inter-location COV | Deviation from mean | |
|---|---|---|---|
| | | maximum | minimum |
| 2 km/h | 4.70% | 1.08 | 0.94 |
| 8 km/h | 3.95% | 1.05 | 0.94 |
| 24 km/h | 2.95% | 1.05 | 0.97 |

For the real-time measurement, this study used two particle counters (Model CI-500, Climet Instruments Co. Redlands, CA) that count the particles in six size ranges: 1 ~ 5 μm, 5 ~ 7 μm, 7 ~ 9 μm, 9 ~ 11 μm, 11~ 14 μm and >14 μm, in real time. One of the units was used as a reference at a fixed sampling location and the second unit to measure the nine evenly-distributed points in the cross sectional area. Since dust concentration was not constant, the reference unit was used to correct the readings from the movable unit. The ratio of the particle count from movable particle counter to the particle count from the reference particle count is an indication of the relative concentration level of the specific location compared to the fixed point. The inter-location variance of the non-dimensional ratio evaluates the spatial uniformity of the concentration profile. In this study, the averaged ratio particle counts from 3 replicated experiments were used as the representative relative concentration for the specific location.

Low COVs of <10% for six particle size ranges (Table 5) showed that our wind tunnel maintains a uniform concentration profile.

Table 5. The COV for the uniformity of particle counts of dusts.

| Velocity | Dust | 1 - 5 um | 5 - 7 um | 7 - 9 um | 9 - 11 um | 11 - 14 um | > 14 um |
|---|---|---|---|---|---|---|---|
| 8 km/h | Arizona road dust | 2.5% | 2.5% | 2.6% | 2.6% | 3.0% | 4.6% |
| 2 km/h | fly ash | 6.4% | 6.3% | 3.9% | 3.7% | 4.9% | 6.5% |
| 8 km/h | fly ash | 4.0% | 4.6% | 2.5% | 1.9% | 2.0% | 3.2% |
| 24 km/h | fly ash | 7.2% | 2.1% | 3.4% | 4.2% | 5.9% | 9.5% |

.The particle size distribution (PSD) of the dust collected in the filters was analyzed using a Beckman Coulter Counter Multisizer (CCM) (Module TM 3, Beckman Coulter, Fullerton, CA ). The CCM is calibrated by the manufacturer annually and by laboratory technicians every 100 runs. One experiment was done at 8 km/h. The inter-location COV for the MMD of Arizona road dust in the cross sectional area was less than 5% horizontally and vertically indicating the spatial uniformity of the PSD of the dust.

## Conclusions

In conclusion,

- A new dust wind tunnel which has a cross-sectional area of 1m x 1m was built,
- A vibration hopper was designed to feed dust into the wind tunnel at feed rates from 0.1 ~100 g/min,
- A dust-loss collector was designed to recover more than 90% of the dust lost to the sampler's inner surface.
- Wind velocity in the dust wind tunnel is uniform within 10% of the mean (COV< 3%) for wind speeds of 2, 8 and 24 km/h.
- The dust concentration in the test section of the tunnel is was uniform within 10% (COV<7%) for wind speeds of 2, 8 and 24 km/h, and
- The inter-location COV for the MMD of Arizona road dust in the cross sectional area was less than 5% horizontally and vertically at the wind speed of 8km/h.

This study indicated that both the air flow velocity and PM concentration were uniformly distributed throughout the cross-sectional area. Furthermore, the vacuum technique has proven to be an effective way to recover the dust lost to the inside wall of the sampler inlet. The Center for Agricultural Air Quality Engineering and Science (CAAQES) will begin investigating the performance of PM (particulate matter) samplers in the new dust wind tunnel.

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