Fugitive Dust Generation in the Laboratory

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Introduction

Fugitive dust (dust composed of natural materials, suspended into the air by human activities) is an air quality concern in many agricultural regions of the United States. Fugitive dust is generated almost everywhere by vehicles traveling on unpaved or sediment-covered roads and at construction and waste management sites (Cowherd *et al*., 1988). In the Southern High Plains of Texas and the Columbia Plateau of Washington State, most fugitive dust is generated by wind erosion. In the San Joaquin Valley of California, agricultural operations on land surfaces are the primary source of fugitive dust.

Generation, collection and measurement of dust in a controlled laboratory setting can be an important tool for determining the specific physical and chemical source characteristics of airborne particulate matter, regulated under United States Environmental Protection Agency PM_{10} (airborne particles smaller than 10 mm) and $PM_{2.5}$ (particles smaller than 2.5 mm) standards, as well as by individual states and air pollution control agencies.

There is extensive literature regarding the production and measurement of dust aerosols in the laboratory, although these publications generally reflect instruments and experiments not designed to investigate ambient fugitive dust. Most work has instead focused on process control or occupational hygiene in manufacturing (Heitbrink *et al*., 1990), inhalation toxicology (Shiotsuka *et al*., 1992), and the pharmaceutical industry (Hindle and Byron, 1995). Still, many techniques, equipment, and findings of these types of studies can be applied to research on atmospheric fugitive dust. Cowherd and Grelinger (1992) provided a good description of some laboratory systems used to generate and measure fugitive dust, while Gill *et al*. (in press) have developed a comprehensive review of the theory and practice of dust aerosol production in laboratory settings.

Modern laboratory systems for generation and collection of dust as an atmospheric aerosol can be classified into two different categories based on their mode of operation: either
(A) (re)suspend dust from a small amount of source material by fluidization: or
(B) generate dust by applying kinetic energy (through gravitation or mechanical dispersion) to a relatively large source sample.

Most resuspension chambers (category A) create dust in discrete "puffs," and completely collect all or as much of the aerosol as possible. Dust generators (category B) often create dust in continuous "plumes," and sample only a portion of the evolved aerosol. Another significant difference between laboratory dust production systems relates to sample preparation, especially with regards to particle size. Some systems utilize samples in more or less the mixed, polydisperse state they exist in the field; others sieve or preseparate materials into various size fractions before testing for dust production. Certain instruments may be more appropriate than others for measuring different quantities in different experiments. For example, a system of type (A) may be appropriate for complete chemical analysis of particles potentially available for resuspension from a surfacewhile a system of type (B) may be appropriate for a laboratory simulation of a dust monitor downwind of a field undergoing wind erosion.

The Lubbock Dust Generation, Analysis and Sampling System

The Lubbock Dust Generation, Analysis and Sampling System (shown in schematic form in Figure 1) simulates and measures characteristics of particle generation by wind erosion, and collection of aerosols by a filter sampler placed in a very dusty environment. It follows category (B) of the previous section; i.e., a system which generates a large cloud of polydisperse dust by application of kinetic energy to a source sample, and measures a representative portion of the aerosol. The Lubbock system contains three interconnected sections: a controlled-energy dust generator, a dust transport / measurement zone, and a dust settling / aerosol collection chamber.

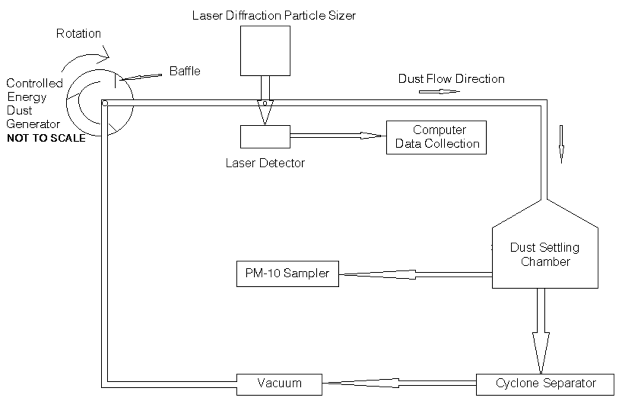

Figure 1. Schematic (<u>not to scale</u>) of Lubbock dust generation, analysis and sampling system.

The Controlled Energy Dust Generator (CE/DG) (Figure 2, A) consists of a rotating metal barrel, 86 cm long and 56 cm in diameter, resting horizontally on four 7.6 cm caster wheels placed on the corners of a 107 cm long by 76 cm wide by 81 cm tall angle iron frame. An electric motor (1.1 kW, 9.6 amp, 172.5 RPM) (Figure 2, B) mounted on the frame rotates the barrel with a V-belt. Three baffles are fixed to the interior barrel surface, and a half-barrel section (fixed to frames outside the barrel), is placed inside the barrel. The barrel is capped by a rigid Plexiglas shield. Samples for dustiness testing are placed inside the barrel, which rotates at a preselected rate; the fixed half-section holds the sample against the baffles until the sample is at the top of the drum, from where it falls to the bottom. A commercial wet-dry vacuum (Figure 2, C) blows air into the barrel through a 2.54 cm diameter metal pipe 6.35 cm above the base of the drum. Holes spaced 2.0 cm apart on the entrance-air pipe promote dust suspension from the falling grains; the dust is entrained into a 2.54 cm pipe in the center of the barrel, with holes spaced 5 cm apart, to exit the dust generator into the transport and settling modules.

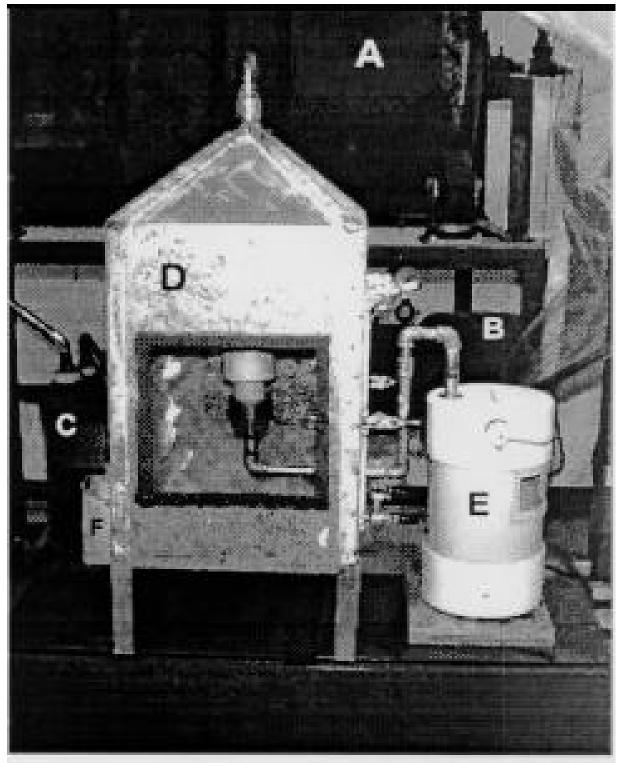

Figure 2. Configuration of the dust generation and settling portions of the Lubbock system. The rotating barrel dust generator (A) is controlled by a variable-speed motor (B) to impart a specific kinetic energy to the dust source sample placed inside it. Airflow provided by a vacuum (C) transports dust through the system, settling into a sampling chamber (D) where fine particles are collected into a PM_{10} sampler (E). Airflow exits the bottom of the settling chamber, passes through a cyclone separator (F) which collects coarse material, and returns to the vacuum.

The CE/DG was developed and used by researchers at Texas Tech University (in collaboration with USDA-ARS scientists) to demonstrate that dust generation from wind erosion is a function of kinetic energy from abrasion, and to investigate the effects of kinetic energy and soil type on dust generation (Singh, 1994; Singh *et al.*, 1994). Kinetic energy of soil particles dropping to the bottom of the drum can be calculated from the height of fall. The "drop shatter test" (Marshall and Quirk, 1950) uses a similar methodology to measure the resistance of soil particles to disaggregation, and has long been used by soil scientists and engineers. The height of fall (50 cm) in the CE/DG causes an impact velocity of 3.12 m/s for the dust source materials, calculated by Singh (1994) to be equivalent to the impact velocity from saltation for a friction velocity of 0.6 m/s (typical of a moderate to strong wind erosion event).

After exiting the dust generator module, dust is transported through a pipe in which it is analyzed for particle size by laser diffraction spectroscopy (Figure 3) before entering the settling chamber (Figure 2, D) wherein an aerosol sampler collects PM_{10} for archival and future chemical analysis. The settling chamber consists of a 45-cm tall rectangular steel box with a 30-cm square base, with a pyramidal top 30 cm by 30 cm by 20 cm from which dusty airflow enters through the transport pipe. The chamber has a glass window on one side, and on other sides removable metal fittings (sealed when secured with stainless steel toggle clamps), to which the inlet module of the aerosol sampler (Figure 2, E) are attached; the PM_{10} sampling head sits inside the settling chamber when operating. PM_{10} is collected using a low-volume impaction aerosol sampler known as the "MiniVol" (AirMetrics, Inc., Springfield, Oregon), which pulls a fraction of the air from the settling chamber at 5 l/min through a 47mm-diameter circular polycarbonate filter. These PM_{10} -bearing filters can be retained and stored, and are ideal for additional microscopic and/or elemental analysis to further investigate the physical and chemical composition of dust from a given sample. Dust exits the settling chamber through another 2.26 cm diameter pipe at the bottom, and is routed into a specially-designed cyclone (Figure 2, F) (Zobeck, 1989) to collect most of the remaining dust particles. The airflow in and out of the system is controlled by valves, and measured with a manometer connected to the piping system on the suction side (Singh *et al*., 1994).

The He-Ne laser beam of a commercial particle sizer (Malvern model 2600) (Figure 3,A) shines through a 15.6 mm hole in the pipe in the "dust transport" region (Figure 3, B) to determine the particle sizes present in the dust cloud before it enters the aerosol sampling chamber. The particle sizer is mounted on a benchtop physically separated from the rest of the system, in order to minimize vibration transfer from the dust generator. The optical and engineering principles of laser diffraction spectroscopy for particle sizing are widely reported elsewhere (e.g. Witt and Röthele, 1996). Briefly, aerosols intersecting light from a He-Ne laser deflect the beam by an amount dependent on factors including particle size. The intensity and position of diffracted light is measured by a multi-element (concentric rings) photodetector (Figure 3, C), converted to a set of electrical currents (one for each element of the detector), digitized, downloaded to a personal computer (Figure 3, D) and converted by proprietary software to a particle size distribution.

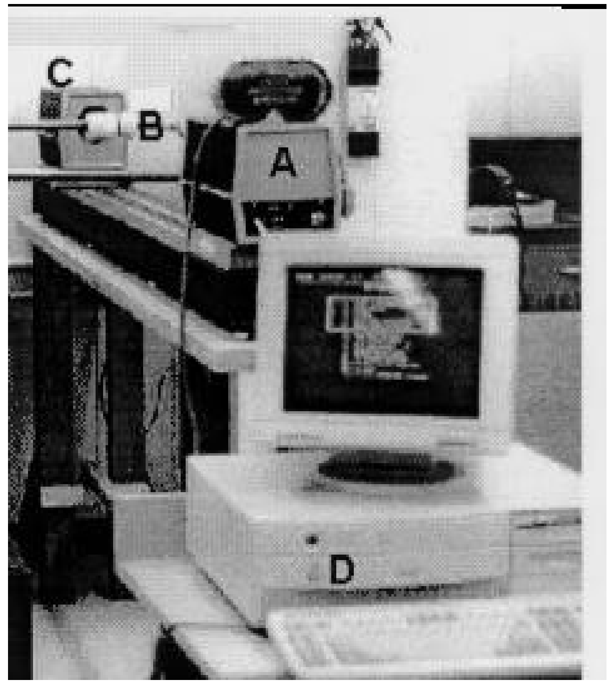

Figure 3. Malvern laser diffraction particle sizer, separated from the rest of the Lubbock system (Figure 2) . The beam of a He-Ne laser (A) shines through a hole in the dust transport pipe (B, covered with sleeve), interacting with aerosols passing between the dust generation and settling chambers. Laser light diffracted by the particles is received by a detector (C), converted into electrical currents, and downloaded to a personal computer (D), which converts the data to particle sizes, stores and analyzes the results.

The inside surface of the dust generator is vacuumed thoroughly and rinsed with clean compressed air prior to testing each sample. The removable dust transport pipes are rinsed with clean air at high pressure, after closing the measuring-zone hole by covering with a tight sleeve (Figure 3, B). The inside surfaces of the settling chamber are wiped down and rinsed with clean compressed air, and the cyclone is cleaned and emptied as necessary. The aerosol sampler is cleaned according to standard protocols, and the particle-bearing membrane filter is changed after each run. Quality assurance tests with the CE/DG indicate that these steps result in an aerosol concentration through the system indistinguishable above "background" concentrations, and essentially undetectable amounts of dust entering the settling chamber when the system is run without a dust source sample. Before each sample run, the laser diffraction instrument is calibrated to a new "background" spectrum of ambient air in the laboratory.

Materials and Methods

In 1996, we used this system to generate and analyze dust from wind-erodible land surfaces in the Southern High Plains of Texas. In collaboration with USDA-Natural Resources Conservation Service Soil Conservationists, we identified highly-wind-erodible agricultural soils, unpaved roads, and active aeolian landforms (sand dunes and dry saline playa lake surfaces). Samples of dust source material were collected from the top 10 cm of soil surfaces with a shovel, after the first 2 cm was removed (to preclude contamination). For unpaved roads, loose materials were removed from the surface with a plastic broom. All samples were stored in plastic zip-lock type bags. After being returned to the laboratory, the materials were air-dried to less than 2% moisture content, sieved to remove particles >2 mm in diameter, and large clods were crushed to pass the 2 mm sieve. Textural classifications of each soil sample were determined by the Texas Tech University Department of Plant and Soil Science.

The dust generation, analysis and sampling system shown in Figures 2 and 3 was run under a set of standard conditions. Four hundred grams of each sample was spread in the bottom of the dust generator barrel. The CE/DG rotated at 13.3 rpm (40 impacts per minute). Thirty seconds after rotation began, the laser diffraction particle sizer and PM_{10} sampler were activated and run for 5.0 additional minutes. Nominal air inflow to the CE/DG was 0.4 m^3/min, providing PM_{10} concentrations in the settling chamber which could exceed 300,000 æg/m^3, and collecting milligrams of dust on the polycarbonate filter of the aerosol sampler. This is the same order of fine dust concentration measured by Hjemsted and Schneider (1996) for powdered alumina using a European standard rotating-drum dustiness tester, and in the range of what has been measured under intense wind erosion conditions within the source area of a strong dust storm (Nickling and Gillies, 1993) or within a dust plume behind a pickup truck on an unpaved road (Pinnick *et al.*, 1985). In no case was this enough for the PM_{10} sampler orifice to clog and the flow rate of air through the aerosol sampler to drop.

Since fugitive dust particles were expected to be multimodal in size distribution, the laser diffraction spectrometer was run in the "model independent" mode (Hamidi and Swithenbank, 1986). Two separate laser particle size datasets were collected for each sample, starting at 30 seconds and 180 seconds after the CE/DG began operation, respectively. Each individual dataset represented a period of approximately 90 seconds of dust transport out of the CE/DG and 32,767 individual observations of dust particle size (light scattered onto the detectors), the maximum allowed by the Malvern software. Other standard operating procedures of the laser diffraction spectrometer included use of the 100 mm lens, and particle-in-air mode.

After each run, the PM_{10} sampler was removed through the windowed door of the settling chamber, and the dust-containing polycarbonate filter was removed and post-weighed on an analytical microbalance using standard gravimetric analysis protocols. The system was cleaned, and a new filter was placed into the PM_{10} sampler for the next run. The PM_{10} filters were retained after weighing.

Two mean dust particle sizes for each sample were calculated directly by the laser diffraction spectrometer's software, based on a volume-weighted size distribution; (1) represents the first set of 32,767 particle size measurements collected for a given sample (0.5 to 2.0 minutes after the CE/DG started rotating), and (2) represents the second set of 32,767 particle size data points collected for the sample (3.0 to 4.5 minutes after the CE/DG started rotating). A "PM_{10}/total dust" ratio was calculated from the Malvern software's particle size output data, by deriving a cumulative probability distribution of the airborne dust cloud from statistical analyses of volume-weighted particle size data provided by the laser diffraction system (Zobeck *et al.*, 1997) for the first set of particle size data. PM_{10} concentrations within the settling chamber were calculated using gravimetric analysis of the mass of PM_{10} on the filters (µg) collected in the PM_{10} sampler, and the volume of air pulled through the sampler (5 liters/minute * 5 minutes sampling time).

Results and Discussion

Over 300 separate runs of the dust generator were made, representing multiple replicates of samples collected from over 80 sites. Although a detailed discussion of sample selection and interpretation of the entire dataset is beyond the scope of this paper, representative results for samples in several different sedimentary and textural categories are given in Table I.

The fine sandy loams produced much more dust (significantly higher PM_{10} concentrations) than the sand or the clay did. Of the two fine sandy loams, the Drake soil is a difficult to manage, extremely wind-erodible, highly calcareous soil developed on stabilized lunettes (dunes along edges of playa lake beds, composed of silt- and sand-sized agglomerates of finer particles); it produced a higher concentration of PM_{10} than the Amarillo soil (an intensively-farmed soil which covers much of the Southern High Plains) of the same texture, had a smaller mean dust particle size, and had a higher fraction of the total amount of airborne dust in the PM_{10} fraction. The calcareous aggregates in the silt fraction of the Drake soil are much less stable than those of the Amarillo soil, have a lower binding energy, and are thus probably more easily disaggregated into fine dust.

Land Use	**Soil series/texture or road type: location**	**Mean dust particle size, mm , +/- 1 s : (observation #)**	**PM_{10} / Total Dust Ratio**	**PM_{10} Concentration (mg/m^3)**
Irrigated cotton (fallow), conventional till	Amarillo fine sandy loam Dawson County, Texas	31.3 ± 22.1 (1) 28.3 ± 19.6 (2)	.16	260,000
Dryland Sudan grass (fallow), reduced till	Drake fine sandy loam Lubbock County, Texas	25.6 ± 18.5 (1) 23.7 ± 19.2 (2)	.20	300,000
Unvegetated saline playa (large dry lake bed)	Randall clay Lynn County, Texas	34.6 ± 23.3 (1) 23.2 ± 18.9 (2)	.15	37,000
Active dune (abandoned ag. land)	Tivoli fine sand Terry County, Texas	24.1 ± 17.2 (1) 19.9 ± 15.5 (2)	.28	110,000
Unpaved road	Hard-packed earth roadbed with caliche ($CaCO_3$) sand Terry County, Texas	37.0 ± 44.9 (1) 44.7 ± 50.2 (2)	.29	310,000

TABLE I. Representative results obtained with the Lubbock dust generation, sampling and analysis system for wind-erodible land surfaces in the Southern High Plains of Texas.

Although the Randall clay soil nominally contains a predominance of grains apparently in the PM_{10} size range when dispersed in water, in the dry state clay-sized particles are bound into coarse aggregates of much larger size (note that their initial mean dust particle size was the largest of any of the soils tested). The mean dust particle size decreased most rapidly with time for the clay soil than any of the other soils. Even though the clay soil was most readily disaggregated with time, this process did not proceed fast enough over 5 minutes (200 impacts) to produce as high a concentration of PM_{10} as the other samples did.

The fine sand produced a lower concentration of dust than the sandy loams, but that dust which it did produce was the finest in overall size. The sand grains themselves are large, non-suspendible silicate mineral clasts which are quite resistant to large-scale breakage, explaining the lesser proportion of coarser dust. However, quartz sands are subject to removal of small pieces by gouging and breaking off corners during erosion (Krinsley and Doornkamp, 1973), and may also possess loosely-bound secondary mineral coatings which can be dislodged by impacts. Gomes *et al*. (1990) showed that these mechanisms can produce extremely fine aerosols from sand grains.

The unpaved road sample was much more "dusty" overall than any of the soil samples. The PM_{10} concentration was highest for the unpaved road, as well as the fraction of the overall suspended material in the PM_{10} range. However, note that the roadbed's mean dust particle size was also larger, actually increasing with time; and the unpaved-road particle size distribution was extremely skewed, indicating distinct and highly separated "peaks" of very fine and very coarse suspended particles. Roadbeds contain extremely fine particles created from repeated crushing by tires and road maintenance machinery, as well as materials from the wear of brake linings, tires and other vehicular components; this may explain the high overall amount of PM_{10}, and its quick initial release in the dust generator. However, the controlled-energy dust generator imparts much smaller particle separation forces than a vehicle tire or road grader does, so it may not have been able to further disaggregate the remaining particles not already pulverized on the roadbed (and released at the start of the run); thus the coarser overall dust size and the apparent coarsening with time of the dust that was released. These results show that unpaved roads should not be treated in the same way as bare soil surfaces when considering the release of fugitive dust.

Conclusions

We used the Lubbock controlled-energy dust generation, analysis and sampling system to perform a laboratory study of the production of mineral dusts by wind erosion on the Southern High Plains. Since different dust generators often utilize different physical principles, care must be used in comparing these results to those of dust produced from other devices using other samples. Nevertheless, we have shown that a laboratory dust generation and analysis system operating under standardized conditions can provide useful data on the dust produced by different source types, and can generate aerosol samples which would then be available for subsequent chemical analysis and source apportionment of particulate matter.

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