MEASURING CATTLE FEEDLOT DUST USING LASER DIFFRACTION ANALYSIS

H. B. Gonzales, R. G. Maghirang, J. D. Wilson, E. B. Razote, L. Guo

ABSTRACT. *Considerable amounts of particulate matter (PM), including total suspended particulates (TSP), particulates with equivalent aerodynamic diameter less than or equal to 10 μm (PM_{10}), and particulates with equivalent aerodynamic diameter less than or equal to 2.5 μm ($PM_{2.5}$), are emitted from large beef cattle feedlots. Particle size distribution and concentrations of TSP, PM_{10}, and $PM_{2.5}$ at a commercial cattle feedlot in Kansas were measured over a two-year period. The feedlot had a capacity of 30,000 head with a total pen area of 50 ha and was equipped with a sprinkler system for dust control. Collocated low-volume samplers for TSP, PM_{10}, and $PM_{2.5}$ were used to measure concentrations of TSP, PM_{10}, and $PM_{2.5}$ at the upwind and downwind edges of the feedlot. A laser diffraction (LD) analyzer (Beckman Coulter LS 13 320) was utilized to determine the particle size distribution of dust samples collected by TSP samplers. A micro-orifice uniform deposit impactor (MOUDI) was also used to measure particle size distribution at the downwind edge of the feedlot. Considering the same effective size range, the LD analyzer and MOUDI did not differ significantly in mean geometric mean diameter (GMD) (11.6 vs. 13.0 μm) and in mean geometric standard deviation (2.3 vs. 2.3). Wind speed and period of sampling significantly affected the mean GMD of the particles. The PM_{10} and $PM_{2.5}$ concentrations that were calculated from the LD method and TSP data were not significantly different from those measured by low-volume PM_{10} and $PM_{2.5}$ samplers (122 vs. 131 μg m^{-3} for PM_{10} and 26 vs. 35 μg m^{-3} for $PM_{2.5}$). Both PM_{10} and $PM_{2.5}$ fractions decreased as pen surface water content increased, but the $PM_{2.5}/PM_{10}$ ratio showed little change as pen surface water content increased.*

Keywords. *Cattle feedlot, Geometric mean diameter, Laser diffraction, Particle size distribution.*

Open beef cattle feedlots can emit considerable amounts of particulate matter (PM), including total suspended particulates (TSP), PM with equivalent aerodynamic diameter of 10 μm or less (PM_{10}), and PM with equivalent aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$). The combined effects of warm temperature, low humidity, and high wind speed promote rapid water evaporation from the pen surface, making particulates susceptible to suspension via wind scouring and cattle hoof action (Amosson et al., 2006).

Emitted particulates have health and environmental effects. Small particles, particularly $PM_{2.5}$, can be inhaled and deposited in human lung tissue, resulting in respiratory ailments (Saxton et al., 1999). Epidemiologic researchers have noted that $PM_{2.5}$ poses greater risk to human health, resulting in vascular inflammation and atherosclerosis (Pope et al., 2002) and increased incidence of asthma (Gilmour et al., 2006) and other respiratory infections (Dockery et al., 1993; Gordian et al., 1996; Schwartz and Dockery 1992). Because of their risks to human health and environment, National Ambient Air Quality Standards (NAAQS) have been established for PM_{10}, $PM_{2.5}$, and five other criteria pollutants (USEPA, 1987).

Agricultural sources, including beef cattle feedlots, generally have not been included in the implementation of NAAQS; however, agricultural operations are now being considered (USEPA, 2004). Implementation of NAAQS calls for direct measurements of PM_{10} and $PM_{2.5}$ concentrations using PM samplers equipped with size-selective inlets. A possible alternative is indirect determination of PM_{10} and $PM_{2.5}$ concentrations from particle size distribution, especially when samplers with size-selective inlets are not readily available. Knowledge of particle size distribution is also important in determining the fate and transport of PM emitted from animal feeding operations (AFOs) and in development and evaluation of abatement measures for mitigating PM emissions.

Research measuring size distribution of cattle feedlot dust has been limited (Sweeten et al., 1988; Sweeten et al., 1998; Guo et al., 2011). Sweeten et al. (1988) reported a mass median diameter (MMD) of 10.9 ± 1.4 μm for TSP in a cattle feedlot in Texas using a Coulter Counter (model TAII, Beckman Coulter, Inc., Fullerton, Cal.). A related study of three cattle feedlots in Texas by Sweeten et al. (1998) showed

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MMDs of 9.5 ± 1.5 μm for TSP samplers and 6.9 ± 0.8 μm for PM_{10} samplers. Hamm (2005) also used a Coulter Counter (Multisizer 3, Beckman Coulter, Inc., Fullerton, Cal.) to determine the particle size distribution in a cattle feedlot in Texas; he reported mean MMD of 16.0 μm, geometric standard deviation (GSD) of 2.1, and PM_{10}/TSP ratio of 0.28. Guo et al. (2011) measured particle size distribution downwind of a feedlot in Kansas using a micro-orifice uniform deposit impactor (MOUDI) and reported geometric mean diameters (GMDs) ranging from 7 to 18 μm.

Instruments for measuring particle size distribution include cascade impactors (Guo et al., 2011), aerodynamic particle sizers (Reid et al., 2008), and Coulter Counters (Sweeten et al., 1988; Sweeten et al., 1998; Hamm, 2005). Another potential method is using laser diffraction, which is widely used in the medical field because of its relative ease of operation, high speed, and wide range of size determination (Xu, 2000). Laser diffraction has the potential to enhance measurement of size distribution and concentrations of various size fractions in AFOs, including cattle feedlots. Research in other fields has compared laser diffraction with other techniques, including cascade impactors, using nebulized aerosols (Kwong et al., 2000) or powder aerosols (Martin et al., 2006), which showed good linear correlation (R^2 = 0.96), especially in the fine particle fraction. In agricultural operations, Cao (2009) compared laser diffraction particle size analyzers (models LS 13 320 and LS 230, Beckman Coulter, Inc., Miami, Fla.), a laser scattering particle size analyzer (model LA-300, Horiba Instruments, Inc., Irvine, Cal.), and a Coulter Counter Multisizer 3 (CCM 3, Beckman Coulter, Inc., Miami, Fla.) in measuring the particle size distribution in a poultry layer operation. No significant difference occurred between the values obtained using the LS 13 320 and LS 230. The greatest mean MMD value was from the LA-300 (22.6 ±2.7 μm), and the smallest mean MMD was from the CCM 3 (14.0 ±0.7 μm). Mean GSDs were 2.67 ±0.11 μm (for LS 13 320), 1.99 ±0.15 μm (for LA-300), 1.84 ±0.04 μm (for CCM 3), and 2.65 ±0.22 μm (for LS 230).

Clearly, more research is needed to measure particle size distribution in open beef cattle feedlots. This research is expected to contribute to the still limited data on particle size distribution, not only in cattle feedlots but also in other AFOs. The objectives of this research were to:

- Measure the size distribution of PM emitted from a beef cattle feedlot while comparing the laser diffraction (LD) method and the cascade impactor.
- Compare PM_{10} and $PM_{2.5}$ concentration measure–ments using the LD method and gravimetric samplers.
- Determine the effects of meteorological factors and sampling period on particle size distribution.

Material and Methods

Feedlot Description

This research was conducted from July 2007 to July 2009 at a commercial cattle feedlot in Kansas. The feedlot contained approximately 30,000 head in pen area of 50 ha. The feedlot had a water sprinkler system that was operated for dust control from April to October and during prolonged dry periods. Pens were cleaned two to three times per year, and manure was removed at least once per year.

Prevailing wind directions at the feedlot were south-southeast during summer and north-northwest during winter. During the measurement period (July 2007 to July 2009), measured wind directions were 64% from the south, 8% from the north, 14% from the east, and 14% from the west. Average annual precipitation was 540 mm. Daily air temperature ranged from -16°C to 31°C with an average of 12°C. Daily wind speed ranged from 0.55 to 12.9 m s^{-1} with an average of 4.6 m s^{-1}.

Particulate Sampling and Measurement

Gravimetric low-volume (LV) samplers, equipped with size-selective inlets for TSP, PM_{10}, and $PM_{2.5}$, were set up at the north and south edges of the feedlot (for a total of six samplers for both sites). Measurement height was 2.2 m. The north and south sampling sites were located approximately 3 and 30 m, respectively, from the closest pens. These sampling sites were selected based on the prevailing wind direction so that samplers were able to capture PM coming from the feedlot; power availability and access to the sampling sites were also considered.

Before field sampling, each sampler was audited for flow and tested for leaks. Each sampler had a cartridge equipped with a polytetrafluoroethylene (PTFE) filter (Whatman, Inc., Clifton, N.J.) that was placed in a conditioning chamber (at 25°C and 40% RH) for 24 h prior to weighing before and after sampling. During sampling, the LV samplers were operated for 12 h at a flow rate of 5 L min^{-1}. There were 48 sampling days during the two-year measurement period,

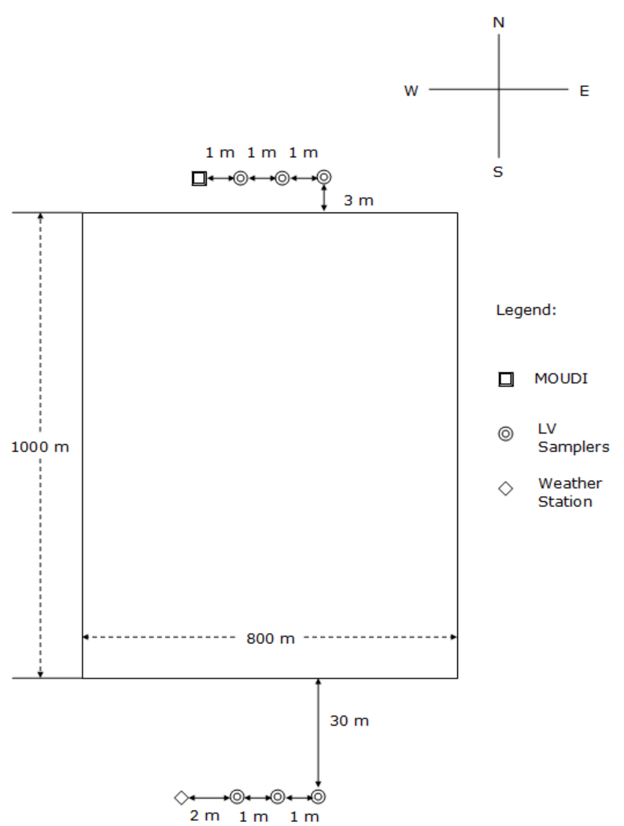

Figure 1. Schematic of the feedlot showing relative locations of samplers and weather station (not to scale).

and two 12 h samples were collected with the LV samplers for each sampling day, for a total of 96 samples each for TSP, PM_{10}, and $PM_{2.5}$. Particulate mass was determined from the difference in the masses of the conditioned filter before and after sampling. The concentration was calculated as the mass of PM collected divided by the total volume of air sampled.

Particle Size Distribution

Particle size distribution was measured using a MOUDI (model M100/110R, Thermo Fisher Scientific, Inc., Franklin, Mass.) and an LD analyzer (model LS 13 320, Beckman Coulter, Inc., , Fullerton, Cal.). The MOUDI was collocated with the LV samplers at approximately 2.2 m above the ground at the north sampling site (typically the downwind location). In addition, particles collected on the filters from the LV samplers for TSP were analyzed with the LD analyzer.

The MOUDI was operated in six stages with cutpoint diameters of 18, 9.9, 6.2, 3.1, 1.8, and 0.9 μm. The upper five stages had aluminum foil substrates (MSP, Shoreview, Minn.), whereas the bottom filter was a PTFE filter (Whatman, Inc., Clifton, N.J.). The PTFE filter was conditioned for 24 h in a conditioning chamber (at 25°C and 40% RH) prior to weighing before and after sampling. The aluminum foil substrates were lightly greased to prevent particle bounce, baked in an oven for 90 min at 65°C, and conditioned for 24 h prior to weighing before sampling. The MOUDI was operated for 24 h at a flow rate of 30 L min^{-1} to ensure that measurable amounts of PM were collected on each impactor stage. The LV samplers with PTFE filters used for LD analysis were operated simultaneously with the MOUDI (24 h) at a flow rate of 5 L min^{-1}. During the two-year measurement period, there were forty-eight 24 h samples for the MOUDI. The geometric mean diameter (GMD) and the geometric standard deviation (GSD) were calculated using the following equations (Hinds, 1999):

$$\mathrm{GMD} = \exp\left[\frac{\sum\left(m_j \ln d_j\right)}{\sum m_j}\right] \tag{1}$$

$$\mathrm{GSD} = \exp\left[\frac{\sum\left\{m_j\left[\ln\left(\frac{d_j}{\mathrm{GMD}}\right)\right]^2\right\}}{\sum m_j}\right]^{0.5} \tag{2}$$

where m_j is the mass fraction of particles in the jth stage of the MOUDI, and d_j is the geometric mean diameter of particles in the jth stage of the MOUDI (μm).

The LD analyzer had an operating size range of 0.4 to 2000 μm. It had a universal liquid module that could be operated with a variety of dispersing media (dispersants). Operation of the instrument involved the initial step of preconditioning a monochromatic beam (laser) before passing it through a group of particles within the sample module (Beckman Coulter, 2003). Blueprints of the scattered light were then measured by various detector elements connected in series at different angles. The signals detected were converted to a known particle size distribution using a model-based matrix that contains computed detector signals per unit volume of spherical particles.

Preliminary tests showed that at least 1 mg of dust particles was needed to achieve the desired obscuration range of 8% to 12% (Beckman Coulter, 2003). High particle concentration promotes multiple scattering, increasing the probability the same particle will scatter light multiple times before reaching the detectors. Too low of a concentration and obscuration could lead to low signal-to-noise ratio and poor repeatability.

Particles from each filter of the TSP samplers were initially extracted by washing the filter with isopropyl alcohol, which was used as the dispersant in the LD analyzer to minimize particle aggregation. Isopropyl alcohol was selected for the suspension solution based on preliminary tests and previous research (Boac et al., 2009; Cao, 2009). The washed filters were dried and conditioned for 24 h prior to weighing to obtain the mass of filter after washing. The resulting dust-isopropyl alcohol mixture was transferred to a 50 mL plastic centrifuge tube and centrifuged for 5 min at 4000 rpm using a high-capacity centrifuge (Precision Durafuge 300, Thermo-Fisher Scientific, Inc., Waltham, Mass.). Excess isopropyl alcohol was decanted, leaving about 15 mL of dust suspension, which was then agitated using a vortex mixer (Sybron Thermolyne Maxi Mix, Thermolyne Corp., Dubuque, Iowa).

A micropipette was used to transfer drops of the dust suspension to the LD analyzer universal liquid module until the recommended obscuration of 8% to 12% was attained. The instrument was programmed to conduct a 90 s sonication prior to analysis to minimize clumping or aggregation of the dust sample and two replicates, followed by a 60 s analysis for each subsample. The 90 s sonication period was selected based on previous research with the same LD analyzer (Pearson et al., 2007; Boac et al., 2009).

The instrument software was used to obtain size distribution statistics (volume distribution including the GMD and GSD) based on equivalent sphere diameter (d_p). The equivalent aerodynamic diameter (d_a) was calculated using the following relationship (Hinds, 1999):

$$d_a = d_p\sqrt{\frac{\rho_p}{\rho_o}} \tag{3}$$

where ρ_o is unit density (1.0 g cm^{-3}), and ρ_p is particle density (g cm^{-3}). Mean particle density was 1.8 ±0.1 g cm^{-3}, based on measurements with a multipycnometer (model MVP-1, Quantachrome Corp., Syosset, N.Y.).

From laser diffraction data, the GMD and GSD were calculated using equations 1 and 2 and for the effective size range that corresponded to the operating size range of the MOUDI. In addition, from the particle size distribution data derived from the laser diffraction analyzer and measured TSP concentration, the $PM_{2.5}$ and PM_{10} concentrations were determined using two methods. In the first method, herein referred to as the cumulative fraction method, the concentration was obtained as the product of the cumulative mass fractions and TSP concentration, that is:

$$PM_{10} = F(10)\ TSP \tag{4}$$

$$PM_{2.5} = F(2.5)\ TSP \tag{5}$$

where F(2.5) is the cumulative mass fraction of particles that are smaller than or equal to 2.5 μm in diameter, and F(10) is the cumulative mass fraction of particles that are smaller than or equal to 10 μm in diameter. The second method, herein referred to as the particle fraction method, used empirical expressions (Hinds, 1999) that corresponded to U.S. EPA guidelines on size-selective sampling. The fraction of particles of diameter d_a that are included in the $PM_{2.5}$ fraction ($PF_{2.5}$) was computed for the LD data using the following empirical expression (Hinds, 1999):

$$PF_{2.5} = \left[1 + \exp\left(3.233 d_a - 9.495\right)\right]^{-3.368} \quad (6)$$

In addition, the fraction of particles of diameter d_a (μm) in the PM_{10} fraction (PF_{10}) was obtained using the following equations (Hinds, 1999):

$$\begin{aligned} PF_{10} &= 1.0 && \text{for } d_a < 1.5 \\ PF_{10} &= 0.9585 - 0.00408 d_a^{\,2} && \text{for } 1.5 < d_a < 15 \\ PF_{10} &= 0 && \text{for } d_a > 15 \end{aligned} \quad (7)$$

The PM_{10} and $PM_{2.5}$ concentrations were then calculated as:

$$PM_{2.5} = PF_{2.5}\ TSP \quad (8)$$

$$PM_{10} = PF_{10}\ TSP \quad (9)$$

Weather Conditions and Pen Surface Water Content

A weather station (Campbell Scientific, Inc., Logan, Utah), positioned at 2.5 m above the ground, was used to measure and record atmospheric pressure (model CS100), air temperature and relative humidity (model HMP45C), precipitation (model TE525), and wind speed and direction (model 05103-5) at 20 min intervals in the feedlot.

For each sampling period, manure samples were collected from three randomly selected pens for pen surface water content (WC) determination. Loose manure (about 2.5 to 5 cm) was collected from each pen at various points along the pen center to the feed apron using a trowel and transferred to a sealed plastic bag. The sample WC was determined in accordance with ASTM Standard D2216-98 (ASTM, 2002).

Data Analysis

Particle size distribution and concentration data were screened based on wind direction. An angle of 60° from the centerline of the north and south directions (north was from 0° to 60° and 300° to 360°, and south was from 120° to 240°) was chosen as an acceptable data point because samplers were located at the north and south edges of the feedlot. For the MOUDI, cases in which negative PM mass readings were observed, particularly when concentrations were low, were not considered in the analysis. Data sets also were tested for outliers; data points that had vertical distances exceeding four times the standard error were eliminated (Cornbleet and Gochman, 1979; Lee et al., 2005). Two outliers (out of 16 total data points) for comparison of the MOUDI and LD analyzer were not considered.

In comparing mean values (e.g., MOUDI vs. LD analyzer), assumptions of normality and homogeneity of variances were first tested. If the assumptions were satisfied, then standard statistical tests (e.g., ANOVA, paired t-test, F-test) were applied; otherwise, nonparametric statistical methods were used together with standard tests. In general, both tests showed similar results; as such, results of standard tests are presented here (Montgomery, 1984; Weaver, 2002).

Paired t-tests and F-tests using Microsoft Excel (Microsoft Corp., Redmond, Wash.) were used to compare the MOUDI and LD method in measuring particle size distribution and the LD and LV samplers for PM concentration measurement. Effects of meteorological factors on size distribution were analyzed using the MIXED procedure in SAS (version 9.1.3, SAS Institute, Inc., Cary, NC). The MIXED procedure was chosen to evaluate repeated measures or multiple measure–ments over time on the same feedlot (Wolfinger and Chang, 1995). The same procedure was used to examine the effects of pen surface WC on size distribution, PM concentrations, and PM fractions. Measurements with the LD method were classified according to the operation of the sprinkler system in the feedlot; April to October were considered warm months, while November to March were considered cold months. A 5% level of significance was used for all cases.

Results and Discussion

About 78% of the data points used for the analysis were associated with south wind directions (south was the upwind site; north was the downwind site), and 22% were associated with north wind directions (north was the upwind site; south was the downwind site). During the periods considered, daily temperatures ranged from -3.5°C to 33.7°C with an average of 17.6°C, daily precipitation ranged from 0.00 to 0.31 mm with an average of 0.0084 mm, and daily wind speeds ranged from 1.47 to 12.9 m s^{-1} with an average of 4.51 m s^{-1}.

Cumulative Fraction vs. Particle Fraction Method

Table 1 summarizes the fractions and concentrations from the two methods for the upwind and downwind sampling locations. No significant difference (p-values ranged from

Table 1. Comparison of cumulative fraction and particle fraction methods in determining PM fractions and concentrations.[a]

		Downwind (n = 39)		Upwind (n = 18)	
Size	Method	Fraction ±SEM	Concentration (μg m^{-3}) ±SEM	Fraction ±SEM	Concentration (μg m^{-3}) ±SEM
PM_{10}	Cumulative fraction	0.33 a ±0.01	129 a ±31	0.35 a ±0.02	99a ±19
	Particle fraction	0.31 a ±0.01	123 a ±29	0.33 a ±0.02	92a ±17
$PM_{2.5}$	Cumulative fraction	0.07 a ±0.00	29 a ±7	0.07 a ±0.00	20a ±4
	Particle fraction	0.07 a ±0.00	27 a ±6	0.07 a ±0.00	18a ±3

[a] Mean fractions or concentrations within the same column and particle size followed by the same letter are not significantly different at 0.05 level; n represents the number of acceptable data after screening; SEM is standard error of the mean.

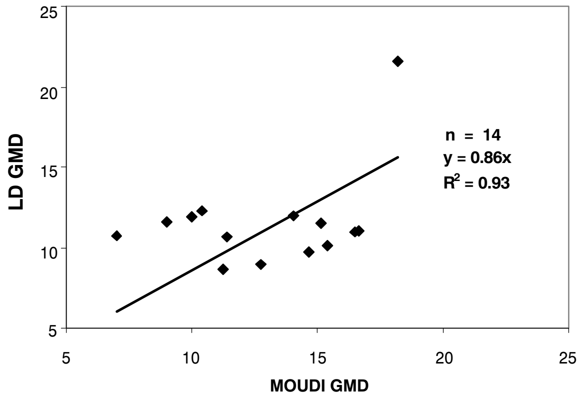

Figure 2. Comparison of the MOUDI and LD analyzer in terms of geometric mean diameters.

0.35 to 0.43) was found in $PM_{2.5}$ and PM_{10} fractions and concentrations calculated using the two methods, indicating that either method can be used to determine PF_{10} and $PF_{2.5}$ fractions and concentrations. For convenience, the cumulative fraction method was then used throughout.

Laser Diffraction vs. Cascade Impactor

For comparison of MOUDI and LD analyzer using the same effective size range, 14 data points were acceptable after screening of data as described previously. Figure 2 shows a strong correlation between GMDs calculated using the LD method and those from the MOUDI. GMDs from the MOUDI ranged from 7.2 to 18.2 μm, with an overall mean of 13.0 μm, and those from the LD analyzer ranged from 8.6 to 21.6 μm, with an overall mean of 11.6 μm. Paired t-test did not show any significant ($p = 0.14$) difference between the GMD values of the MOUDI and LD analyzer. Note that if the full size distribution data from the LD analyzer were considered, the mean GMD was 13.0 μm.

Relatively coarse particles were emitted from the feedlot, as indicated by the large GMDs. The GMDs in this study were higher than those measured by Sweeten et al. (1988) and Sweeten et al. (1998) of 8.5 ± 2.1 μm and 9.5 ± 1.5 μm, respectively. Difference in values could be attributed to the difference in methodology, type of samplers, or feedlot characteristics.

Paired t-test did not also show any significant difference ($p = 0.58$) in mean GSD between the MOUDI and LD. GSD values for the LD method ranged from 1.7 to 2.4, with an overall mean of 2.3. Those for the MOUDI, on the other hand, ranged from 2.1 to 2.9, with an overall mean of 2.3. As expected, if the full size distribution data from the LD analyzer were considered, then the mean GSD (2.9) for the LD method was significantly different from that for the MOUDI.

The LD method and MOUDI also were compared based on the various size ranges used for the MOUDI (table 2). In general, paired t-test did not show any significant difference between the two methods for the various size ranges: >18 μm ($p = 0.10$), 3.1 to 6.2 μm ($p = 0.371$), 1.8 to 3.1 ($p = 0.321$), and 0.9 to 1.8 μm ($p = 0.549$), except for 9.9 to 18.0 μm ($p = 0.0006$) and 6.2 to 9.9 μm ($p = 0.0004$). Difference between the MOUDI and LD method for the two size ranges could be due to several factors. Particle losses were encountered for the LD method during filter washing, as indicated by mean percent recovery for extraction of 93.7% ±1.1%, ranging from 78% to 99%. Percent recovery was calculated by dividing the washed particulate mass (obtained by the mass difference of the filter with dust and the filter after washing off the dust) by the total mass collected during sampling. Other potential sources of error include possible aggregation and deaggregation of particles during the sonication process for the LD method, particle losses or bounce on the MOUDI, and sampling errors associated with the MOUDI and TSP samplers.

Table 3. Downwind and upwind 24 h mass concentrations (μg m^{-3}): laser diffraction (LD) vs. low-volume (LV) samplers.[a]

Site and Method.		Size	*n*	Min.	Max.	Mean	SEM
Downwind	LD	PM_{10}	39	3	679	122	20
		$PM_{2.5}$	39	1	133	26	4
	LV	PM_{10}	39	14	380	131	15
		$PM_{2.5}$	39	7	136	35	5
Upwind	LD	PM_{10}	18	1	223	92	17
		$PM_{2.5}$	18	0.4	43	19	3
	LV	PM_{10}	18	29	212	94	13
		$PM_{2.5}$	18	6	119	28	6

[a] *n* represents the number of acceptable data after screening; SEM is standard error of the mean.

Laser Diffraction vs. Low-Volume Sampler

Table 3 summarizes the $PM_{2.5}$ and PM_{10} concentrations obtained from the LD method and those measured by the LV samplers for the downwind and upwind sampling locations, respectively. For each method, as expected, downwind concentrations were greater than upwind concentrations. Paired t-tests did not show any significant difference (p-values ranged from 0.18 to 0.75) between the LD and LV samplers in both downwind and upwind PM_{10} and $PM_{2.5}$ concentrations. For upwind concentrations, only 18 samples were obtained to compare the LD method and LV samplers because the LD method requires at least 1 mg of sample to achieve the required obscuration level. The slight discrepancies between the values can be attributed to losses during filter washing before LD analysis. In addition, the slightly lower LD measurements could be due to possible agglomeration of the particles during sampling, which could have shifted particle size distribution to a larger size range, thereby decreasing the computed $PM_{2.5}$ and PM_{10} concentration values.

Table 2. Mean mass percentages of size-segregated particles using the MOUDI and laser diffraction method.[a]

Method	Size Range (μm) >18.0	9.9 to 18.0	6.2 to 9.9	3.1 to 6.2	1.8 to 3.1	0.9 to 1.8
MOUDI	38.9 a ±3.9	25.5 a ±2.1	18.5 a ±1.5	10.8 a ±1.6	3.2 a ±0.8	3.2 a ±0.7
Laser diffraction	32.2 a ±3.7	37.7 b ±1.9	12.9 b ±0.9	9.4 a ±0.8	4.0 a ±0.2	3.7 a ±0.3

[a] Mean values for each size range followed by the same letter are not significantly different at 0.05 level.

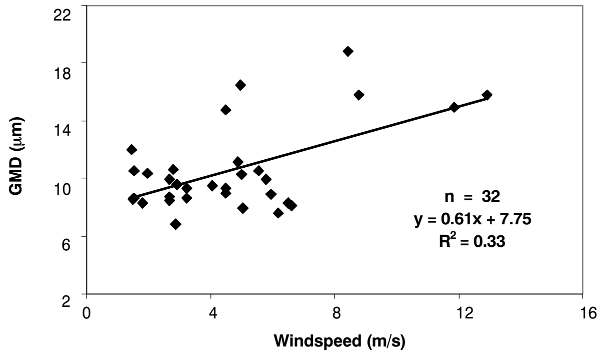

Figure 3. Effect of wind speed on geometric mean diameter obtained from LD method.

FACTORS AFFECTING SIZE DISTRIBUTION

Analysis of LD GMD data with the PROC MIXED procedure in SAS showed that the two main factors affecting GMD were wind speed and time of sampling. Other factors such as temperature, precipitation, and RH did not significantly affect GMD. Figure 3 shows that mean GMD values from the LD method increased slightly with increasing mean wind speed. This result was expected because, as wind speed increases, coarse PM is generated through wind-induced resuspension (Jones et al., 2010), rendering a greater mass of large suspended particles. At low wind speed, resuspension of particles decreased; most of the larger particles settled out after only a short distance, which caused a shift toward smaller particle sizes, thus decreasing mean GMD (Lundgren et al., 1984).

Analysis using F-test for sampling downwind during the warm months showed that mean GMD values were significantly ($p = 0.046$) higher during the daytime ($n = 5$) sampling period (6:00 a.m. to 6:00 p.m.) than during the nighttime ($n = 13$) sampling period (6:00 p.m. to 6:00 a.m.). There were only five values for the daytime sampling period after screening for wind direction. Mean GMDs were 18.2 ±2.7 µm for the daytime sampling period and 14.4 ±1.0 µm for the nighttime sampling period.

Although increased cattle activity, i.e., antagonistic interactions, walking and running behavior (Gonyou and Stricklin, 1984), during the night could cause peaks in dust concentration (Bonifacio, 2009), the average wind speed was smaller during the evening than during the day (4.1 ±0.7 m s^{-1} vs. 5.9 ±0.9 m s^{-1}). A similar observation was reported by Auvermann et al. (2000), who indicated that wind speed decreased during the evening, and the dust plume floated above the feedlot. Note that the considered measurements were taken during warmer months in which water on the pen surface evaporates during the late afternoon due to the daytime temperature, and cattle activity increases because of cooler temperatures in the evening (Amosson et al., 2006). A difference in wind speed greater than 1 m s^{-1} could have affected measured PM concentrations during the day and night sampling. Padgett et al. (2008) reported that large particles dominated the lower portion of the dust plume and deposition occurred closer to the source, whereas smaller particles settled at the upper portion of the plume and traveled at least 100 m away from the source. Because the samplers were about 3 m away from the closest pen (north site), GMD was expected to be large in this study.

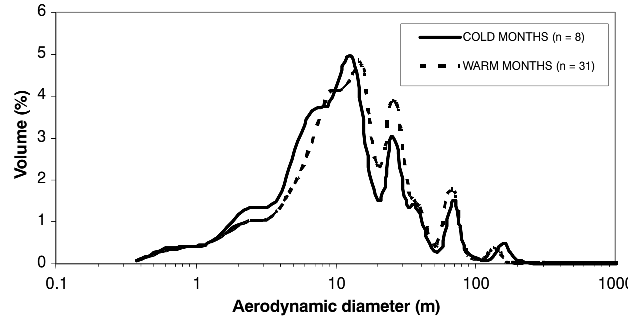

Figure 4. Mean volume percent at different aerodynamic diameters.

WARM VS. COLD MONTHS

Measurements with the LD method during warm months (April to October) and cold months (November to March) were compared (fig. 4). As mentioned previously, the classification of warm and cold months was based on operation of the sprinkler system. During warm months, GMD ranged from 9.2 to 37.5 µm with a mean of 16.2 µm; during cold months, on the other hand, GMD ranged from 10.2 to 21.8 µm with a mean of 13.7 µm. Analysis using F-test showed no significant difference ($p = 0.41$) between measured values during warm and cold months.

EFFECT OF PEN SURFACE WATER CONTENT

Figure 5 shows that concentrations of PM_{10} and $PM_{2.5}$ decreased as pen surface WC increased. Concentrations generally tapered off, starting at 20% WC; this WC level could be considered the threshold WC for dust control. The

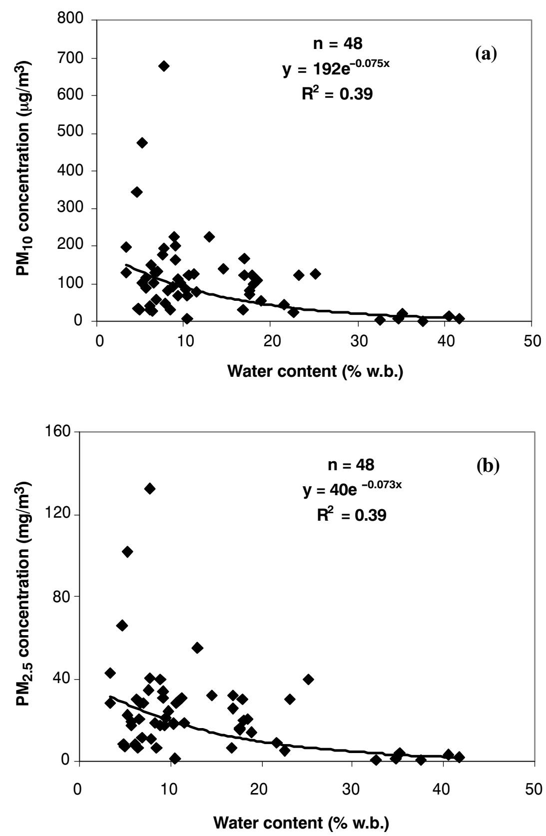

Figure 5. Effects of pen surface water content on PM concentrations measured using the LD method: (a) PM_{10} and (b) $PM_{2.5}$.

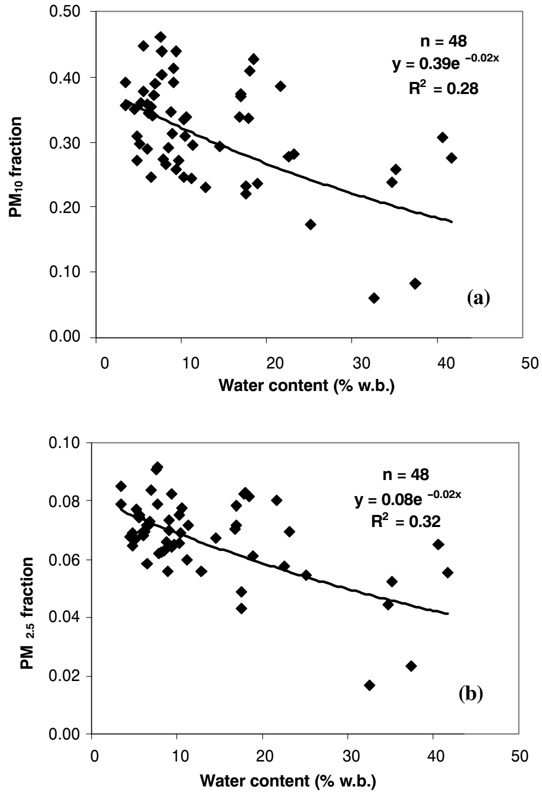

Figure 6. Pen surface water content dependence of PM fractions measured using the LD method: (a) PM_{10} fraction and (b) $PM_{2.5}$ fraction.

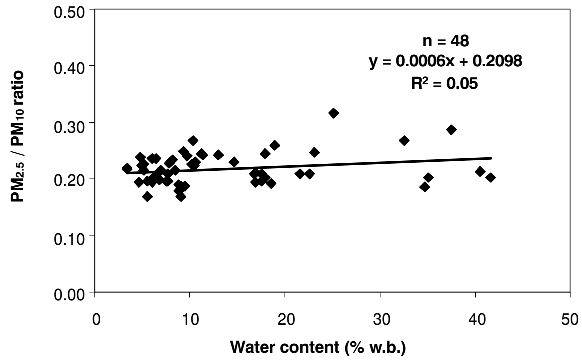

Figure 7. Effect of pen surface water content on $PM_{2.5}/PM_{10}$ ratio measured using the LD method.

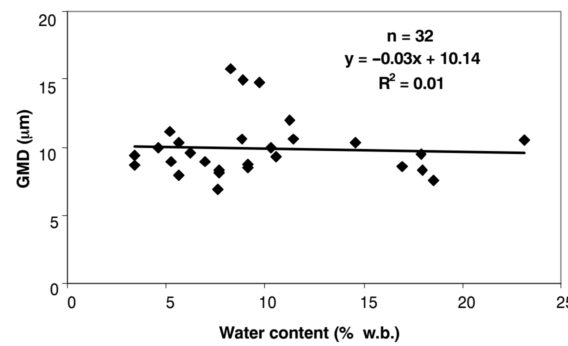

Figure 8. Effect of pen surface water content on mean geometric mean diameter measured using the LD method.

20% threshold WC for the feedlot surface was within what Funk et al. (2008) reported for organic soils and close to the 25% to 30% threshold WC reported by Sweeten et al. (1988) for a cattle feedlot in Texas. Note that excessive water on the pen surface could increase odor and fly problems, whereas too little water promotes dust generation (Davis et al., 1997; Amosson et al., 2006).

PM fractions serve as the basis for predicting long-term emissions from a source (Countess Environmental, 2006). Parameters that reflect size distribution, namely PF_{10} and $PF_{2.5}$ fractions and $PM_{2.5}/PM_{10}$ ratio, were also correlated with the level of pen surface WC. Figure 6 shows that PF_{10} and $PF_{2.5}$ fractions decreased as pen surface WC increased. A weak correlation (R^2 = 0.05) between $PM_{2.5}/PM_{10}$ ratio and pen surface WC was obtained (fig. 7). This was expected because PM_{10} and $PM_{2.5}$ both decreased with increasing pen surface WC. Because the $PM_{2.5}/PM_{10}$ ratio shows the relative precipitation rate of finer particles with respect to coarser particles (Querol et al., 2001; Evagelopoulos et al., 2006), understanding the behavior of finer particles with respect to coarser particles emitted from the feedlot is worthwhile. The $PM_{2.5}/PM_{10}$ ratio from the feedlot ranged from 0.17 to 0.32, with an average of 0.22. This mean value was within the values used for unpaved roads (0.15), agricultural tilling (0.22), and industrial wind erosion (0.40) (Cowherd et al., 2006); however, it was greater than the $PM_{2.5}/PM_{10}$ ratio of 0.11 cited by Countess Environmental (2006) based on the California Air Resources Board (CARB) methodology for PM emissions from cattle feedlots.

The mean GMD obtained from the LD method also was plotted against pen surface WC (fig. 8). The GMD decreased slightly as pen surface WC increased; however, the R^2 value was close to zero, which is similar to the R^2 for the $PM_{2.5}/PM_{10}$ ratio. The slight decrease in GMD implies that emission of coarser particles was minimized as pen surface WC increased. This can be related to the previous finding (fig. 7) in which the $PM_{2.5}/PM_{10}$ ratio slightly increased.

Conclusion

The concentrations and size distribution of particulate matter were measured at a commercial cattle feedlot. The following conclusions were drawn:

- The LD method and MOUDI did not differ significantly in mean GMD (11.6 vs. 13.0 µm) and GSD.
- PM_{10} and $PM_{2.5}$ concentrations derived from the LD method were not significantly different from those measured by low-volume PM_{10} and $PM_{2.5}$ samplers (122 vs. 131 µg m^{-3} for PM_{10}; 26 vs. 35 µg m^{-3} for $PM_{2.5}$).
- The PM_{10} and $PM_{2.5}$ fractions decreased with increasing pen surface WC, whereas the $PM_{2.5}/PM_{10}$ ratio showed little change with pen surface WC.
- Mean wind speed and period of sampling (night vs. day) significantly affected measured GMD of the particles.

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REFERENCES

Amosson, S. H., B. Guerrero, and L. K. Almas. 2006. Economic analysis of solid–set sprinklers to control dust in feedlots. Southern Agricultural Economics Association Paper No. 35341. Griffin, Ga.: SAEA.

ASTM. 2002. D2216-98: Standard test method for laboratory determination of water (moisture) content of soil and rock by mass. In *Annual Book of American Society for Testing Materials Standards*. West Conshohocken, Pa.: ASTM.

Auvermann, B. W., D. B. Parker, and J. M. Sweeten. 2000. Manure harvesting frequency: The key to feedyard dust control in a summer drought. Amarillo, Tex.: Texas Agricultural Extension Service.

Beckman Coulter. 2003. LS 13 320 Laser diffraction particle size analyzer instrument manual. Miami, Fla.: Beckman Coulter, Inc.

Boac, J. M., R. G. Maghirang, M. E. Casada, J. D. Wilson, and Y. S. Yung. 2009. Size distribution and rate of dust generated during grain elevator handling. *Applied Eng. in Agric.* 25(4): 533-541.

Bonifacio, H. F. 2009. Particulate matter emissions from commercial beef cattle feedlots in Kansas. MS thesis. Manhattan, Kans.: Kansas State University.

Cao, Z. 2009. Determination of particle size distribution of particulate matter emitted from a layer operation in southeastern U.S. MS thesis. Raleigh, N.C.: North Carolina State University.

Cornbleet, P. J., and N. Gochman. 1979. Incorrect least-squares regression coefficients in method-comparison analysis. *Clinical Chem.* 25(3): 432-438.

Countess Environmental. 2006. WRAP fugitive dust handbook. Prepared for Western Governor’s Association, Denver, Colo. Available at: www.wrapair.org/forums/dejf/fdh/content/FDHandbook_Rev_06.pdf. Accessed 21 March 2010.

Cowherd, C., J. Donaldson, R. Hegarty and D. Ono. 2006. Proposed revisions to fine fraction ratios used for AP-42 fugitive dust emission factors. Available at: www.epa.gov/ttn/chief/conference/ei15/session14/cowherd.pdf. Accessed 21 March 2010.

Davis, J. G., T. L. Stanton, and T. Haren. 1997. Feedlot manure management. Fort Collins, Colo.: Colorado State University Cooperative Extension. Available at: www.cde.state.co.us/artemis/UCSU20/UCSU2062212202002INTERNET.pdf. Accessed 10 July 2010.

Dockery, D. W., C. A. Pope III, X. Xu, J. D. Spengler, J. H. Ware, B. G. Ferris, and F. E. Speizer. 1993. An association between air pollution and mortality in six United States cities. *New England J. Med.* 329(24): 1753-1759.

Evagelopoulos, V., S. Zoras, A. G. Triantafyllou, and T. A. Albanis. 2006. PM_{10}-$PM_{2.5}$ time series and fractal analysis. *Global NEST J.* 8(3): 234-240.

Funk, R., H. Reuter, C. Hoffmann, W. Engel, and D. Öttl. 2008. Effect of moisture on fine dust emission from tillage operations on agricultural soils. *Earth Surface Proc. and Landforms* 33(12): 1851-1863.

Gilmour, I. M., M. S. Jaakkola, S. J. London, A. E. Nel, and C. A. Rogers. 2006. How exposure to environmental tobacco smoke, outdoor air pollutants, and increased pollen burdens influences the incidence of asthma. *Environ. Health Perspectives* 114(4): 627-633.

Gonyou, H. W., and W. R. Stricklin. 1984. Diurnal behavioral patterns of feedlot bulls during winter and spring in northern latitudes. *J. Animal Sci.* 58(5): 1075-1083.

Gordian, M. E., H. Ozkaynak, J. P. Xue, S. S. Morris, and J. D. Spengler. 1996. Particulate air pollution and respiratory disease in Anchorage, Alaska. *Environ. Health Perspectives* 104(3): 290-297.

Guo, L., R. G. Maghirang, E. B. Razote, S. L. Trabue, and L. McConnell. 2011. Concentration of particulate matter in large cattle feedlots in Kansas. *J. Air and Waste Mgmt* 61: 1025-1035.

Hamm, L. B. 2005. Engineering analysis of fugitive particulate matter emissions from cattle feedyards. MS thesis. College Station, Tex.: Texas A&M University.

Hinds, W. C. 1999. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*. 2nd ed. New York, N.Y.: John Wiley and Sons.

Jones, A. M., R. M. Harrison, and J. Baker. 2010. The windspeed dependence of the concentrations of airborne particulate matter and NO_x. *Atmos. Environ.* 44(13): 1682-1690.

Kwong, W. T. J., S. L. Ho, and A. L. Coates. 2000. Comparison of nebulized particle size distribution with Malvern laser diffraction analyzer versus Andersen cascade impactor and low-flow Marple personal cascade impactor. *J. Aerosol Med.* 13(4): 303-314.

Lee, J. H., P. K. Hopke, T. M. Holsen, and A. V. Polissar. 2005. Evaluation of continuous and filter-based methods for measuring $PM_{2.5}$ mass concentration. *Aerosol Sci. Tech.* 39(4): 290-303.

Lundgren, D. A., B. J. Hausknecht, and R. M. Burton. 1984. Large particle size distribution in five U.S. cities and the effect on a new ambient particulate matter standard (PM_{10}). *Aerosol Sci. Tech.* 3(4): 467-473.

Martin, G. P., H. B. MacRitchie, C. Marriott, and X. M. Zeng. 2006. Characterisation of a carrier-free dry powder aerosol formulation using inertial impaction and laser diffraction. *Pharmaceutical Res.* 23(9): 2210-2219.

Montgomery, D. C. 1984. *Design and Analysis of Experiments*. New York, N.Y.: John Wiley and Sons.

Padgett, P. E., D. Meadows, E. Eaubanks, and W. E. Ryan. 2008. Monitoring fugitive dust emissions from off-highway vehicles traveling on unpaved roads and trails using passive samplers. *Environ. Monitoring and Assess.* 144(1-3): 93-103.

Pearson, T., J. D. Wilson, J. Gwirtz, E. Maghirang, F. Dowell, P. McClusky, and S. Bean. 2007. Relationship between single wheat kernel particle-size distribution and Perten SKCS 4100 hardness index. *Cereal Chem.* 84(6): 567-575.

Pope, C. A., R. T. Burnett, M. J. Thun, E. E. Calle, D. Krewski, K. Ito, and G. D. Thurston. 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *J. American Med. Assoc.* 287(9): 1132-1141.

Querol, X., A. Alastuey, S. Rodriguez, F. Plana, E. Mantilla, and C. R. Ruiz. 2001. Monitoring PM_{10} and $PM_{2.5}$ ambient air levels around primary anthropogenic emissions. *Atmos. Environ.* 35(5): 848-858.

Reid, J. S., E. A. Reid, A. Walker, S. Piketh, S. Cliff, A. Al Mandoos, S. C. Tsay, and T. F. Eck. 2008. Dynamics of southwest Asian dust particle size characteristics with implications for global dust research. *J. Geophysical Res.* 113: D14212.

Saxton, K., D. Chandler, and W. Schillinger. 1999. Wind erosion and air quality research in the northwest U.S. Columbia plateau: Organization and progress. In *Sustaining the Global Farm: Selected Papers from the 10th Intl. Soil Conservation Organization Meeting (ISCO ’99)*, 766-770. E. E. Stott, R. H. Mohtar, and G. C. Steinhardt eds. West Lafayette, Ind.: USDA-ARS National Soil Erosion Laboratory.

Schwartz, J., and D. W. Dockery. 1992. Particulate air pollution and daily mortality in Steubenville, Ohio. *American J. Epidemiol.* 135(1): 12-19.

Sweeten, J. M., C. B. Parnell, R. S. Etheredge, and D. Osborne. 1988. Dust emissions in cattle feedlots. *Vet. Clinics of North America, Food Animal Practice* 4(3): 557-578.

Sweeten, J. M., C. B. Parnell, B. W. Shaw, and B. W. Auvermann. 1998. Particle size distribution of cattle feedlot dust emission. *Trans ASAE* 41(5): 1477-1481.

USEPA. 1987. 40 CFR Part 70: National ambient air quality standards. Research Triangle Park, N.C.: U.S. Environmental Protection Agency. Available at: www.epa.gov/air/caa. Accessed 10 July 2010.

USEPA. 2004. Use of a performance-based approach to determine data quality needs for the PM-coarse (PM_c) standard. Research Triangle Park, N.C.: U.S. Environmental Protection Agency. Available at: www.epa.gov/airnow/particle/pm-colorpdf. Accessed 10 July 2010.

Weaver, B. 2002. Chapter 3: Nonparametric tests. Available at: www.angelfire.com/wv/bwhomedir/notes/nonparpdf. Accessed 14 October 2010.

Wolfinger, R. D., and M. Chang. 1995. Comparing the SAS GLM and MIXED procedures for repeated measures. In *Proc. 20th Annual SAS Users Group Conf.*, 1-11. Cary, N.C.: SAS Institute, Inc.

Xu, R. 2000. *Particle Characterization: Light Scattering Methods*. Particle Technology Series. Dordrecht, The Netherlands: Kluwer Academic.