SIZE DISTRIBUTION AND RATE OF DUST GENERATED DURING GRAIN ELEVATOR HANDLING

J. M. Boac, R. G. Maghirang, M. E. Casada, J. D. Wilson, Y. S. Jung

ABSTRACT. *Dust generated during grain handling can pose a safety and health hazard and is an air pollutant. This study was conducted to characterize the particle size distribution (PSD) of dust generated during handling of wheat and shelled corn in the research elevator of the USDA Grain Marketing and Production Research Center and determine the effects of grain lot, repeated transfer, and grain types on the PSD. Dust samples were collected on glass fiber filters with high volume samplers from the lower and upper ducts upstream of the cyclone dust collectors. A laser diffraction analyzer was used to measure the PSD of the collected dust. For wheat, the size distribution of dust from the upper and lower ducts showed similar trends among grain lots but differed between the two ducts. The percentages of particulate matter (PM)-2.5, PM-4, and PM-10 were 5.15%, 9.65%, and 33.6% of the total wheat dust, respectively. The total dust mass flow rate was 0.94 g/s (equivalent to 64.6 g/t of wheat handled). For shelled corn, the size distributions of the dust samples from the upper and lower ducts also showed similar trends among transfers but differed between the two ducts. The percentages of PM-2.5, PM-4, and PM-10 were 7.46%, 9.99%, and 28.9% of the total shelled corn dust, respectively. The total dust mass flow rate was 2.91 g/s (equivalent to 185.1 g/t of corn handled). Overall, the corn and wheat differed significantly in the size distribution and the rate of total dust generated.*

Keywords. *Grain elevator, Particle size distribution, Geometric mean diameter, Isokinetic sampling, Dust mass flow rate, Particulate matter.*

Dust emitted during grain handling is a safety and health hazard as well as an air pollutant. Grain dust is composed of approximately 70% organic matter, which may include particles of grain kernels, spores of smuts and molds, insect debris (fragments), pollens, and field dust (US EPA, 2003) that become airborne during grain handling (Aldis and Lai, 1979). Due to the high organic content and a substantial suspendible fraction, concentrations of grain dust above the minimum explosive concentration (MEC) pose an explosion hazard (US EPA, 2003). Published MEC values range from 45 to 150 g/m^3 (Jacobsen et al., 1961; Palmer, 1973; Noyes, 1998).

In addition to being a safety hazard to grain elevator workers, grain dust is also a health hazard (NIOSH, 1983). Prolonged exposure to grain dust can cause respiratory symptoms in grain handling workers and in some cases affect workers' performance and sense of well-being (NIOSH, 1983). The American Conference of Governmental Industrial Hygienists (ACGIH, 1997) has defined three particulate mass fractions in relation to potential health effects: (1) inhalable fraction (particulate matter (PM) with a median aerodynamic diameter of 100 µm that enters the airways region), (2) thoracic fraction (PM with a median aerodynamic diameter of 10 µm that deposits in the tracheobronchial regions), and (3) respirable fraction (PM with a median aerodynamic diameter of 4 µm that enters in the gas-exchange regions), herein referred to as PM-4. The US EPA (2007), on the other hand, regulates PM-2.5 or fine PM (i.e., PM with equivalent aerodynamic diameter of 2.5 µm or less) and PM-10 (i.e., PM with equivalent aerodynamic diameter of 10 µm or less). PM-2.5 has been linked to serious health problems ranging from increased symptoms to premature death in people with lung and heart disease. Fine particulates such as PM-2.5, PM-4, and PM-10 are more dangerous in terms of grain dust explosions because MEC generally decreases with decreasing particle sizes (Garrett et al., 1982).

Under the 1990 Clean Air Act, the state environmental agencies are required to regulate the grain elevator industry's emission of airborne dust (US EPA, 1990). The US EPA AP-42 document has listed emission factors for grain elevators (US EPA, 2003). The document cites recent research on dust emission from grain handling operations indicating the mean PM-10 value was approximately 25% of total PM or total dust, and the fraction of PM-2.5 averaged at about 17% of PM-10. Mean PM-10 values for country and export elevators were 20% and 26%, respectively, of total dust (Midwest Research Institute, 1998). The elevators primarily handling wheat had mean PM-10 of about 30% of total dust, whereas those primarily handling corn and soybean had an average PM-10 of slightly less than 20% of total dust.

Several studies have been conducted to determine the amount of dust emitted from external and process emission

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sources in grain elevators (table 1) and measure the particle size distributions (PSD) for dust collected from the same system (table 2). Parnell et al. (1986) reported mass median diameter (geometric standard deviation) of grain dust < 100 μm for corn and wheat of 13.2 and 13.4 μm (1.80 and 2.08), respectively. Martin and Lai (1978) cited mean mass median diameters of residual dust (that sticks to grain) of 13 and 14 μm for wheat and sorghum, respectively. In the same study, the mean percentages of residual dust with diameter ≤ 10 μm were about 34%, 33%, and 45% for sorghum, corn, and wheat, respectively.

Piacitelli and Jones (1992) studied the size distribution of sorghum dust collected by impactors during on-farm handling (harvesting, on-farm storage, delivery truck). Their results indicated that about 2% of the particles had ≤ 3.5 μm aerodynamic diameter; 10% were ≤ 10 μm, 24% were ≤ 15 μm, 48% were ≤ 21 μm, and 52% were > 21 μm.

However, data on the PSD of dust generated during grain handling in a bucket elevator system and the fraction that might be a health hazard are limited (Wallace, 2000). Martin and Sauer (1976) studied the dust fraction that was contaminated by mold spores and fungal metabolites, which can be health hazards to grain elevator workers; however, they did not consider PSD. The most comprehensive PSD study was conducted by Parnell et al. (1986), but their study was limited to dust < 100 μm, the most explosive fraction. Thus, limited data exists on the complete range of particle sizes generated during bucket elevator handling even though this system is the primary grain and feed handling system used in the United States. This study fills the gap where no complete PSD is available for wheat and corn dust, and provides more specific data than previous studies particularly on small particle sizes, PM-2.5 and PM-4.

The objective of this study was to characterize the PSD and dust generated (i.e., mass flow rate) in a bucket elevator system collected upstream of the cyclone separator. The fractions of interest were particles with aerodynamic diameters ≤ 2.5 and ≤ 10 μm for regulatory purposes and ≤ 4 μm for health reasons. Specific objectives were to determine the effects of grain lots (part 1), repeated transfers (part 2), and grain types on PSD of the dust.

Table 1. Published particulate emission factors for grain handling.

	Emission Factor (g/t of grain)		
Emission Source	Total PM	PM-10	PM-2.5
Grain receiving (hopper and straight truck, railcar, barge, ships)	8.30-90.0[a],[b],[c],[d],[e]	0.600-29.5[b],[d],[e]	0.650-5.00[d]
Grain cleaning (internal vibrating - with cyclone)	37.5[b],[d]	9.50[d]	1.60[d]
Headhouse and internal handling (legs, belts, distributor, scale, etc.)	30.5[b],[d]	17.0[b],[d]	2.90[d]
Storage vents	12.5[b],[d]	3.15[d]	0.550[d]
Grain drying (column and rack dryers)	110-1500[b],[d]	27.5-375[d]	4.70-65.0[d]
Grain shipping (truck, railcar, barge, ships)	4.00-43.0[a],[b],[d]	1.10-14.5[b],[d]	0.185-2.45[d]

[a] Kenkel and Noyes, 1995.
[b] Midwest Research Institute, 1998.
[c] Shaw et al., 1998.
[d] US EPA, 2003.
[e] Billate et al., 2004.

Table 2. Published size distribution of grain dust from grain elevators.

Grain Type	Percentage PM Dust of the Total Dust Collected (%)					
	< 125 μm	< 100 μm	< 10 μm	< 8 μm	< 4 μm	< 2.5 μm
Corn	62.0-86.0[a],[b],[c]	54.1[d]	5.00-12.0[e],[f]	5.00-12.0[a]	0.600-3.00[f]	0.200-1.00[f]
Wheat	33.0-78.0[a],[c]	34.3[d]	-	3.00-4.00[a]	-	-
Sorghum	60.0[c]	34.3[d]	-	-	-	-
Rice	-	44.2[d]	-	-	-	-
Soybean	-	50.6[d]	-	-	-	-
Cyclone dust	-	-	9.00[g]	-	-	-
Baghouse dust	-	-	20.0[g]	-	-	-

[a] Martin and Sauer, 1976 (from table 2).
[b] Martin and Stephens, 1977 (from table 1).
[c] Martin and Lai, 1978 (from table 3).
[d] Parnell et al., 1986 (from table 3, paper also gave PSD graphs of dust < 100 μm).
[e] Lai et al., 1984 (interpolated from PSD graph, fig. 5).
[f] Baker et al., 1986 (interpolated from PSD graph, fig. 2).
[g] Martin, 1981 (interpolated from PSD graph, fig. 5).

Materials and Methods

Test Facility

Dust samples from handling of wheat and shelled corn were collected upstream of the cyclone separators in the research grain elevator at the USDA-ARS, Grain Marketing and Production Research Center (GMPRC) (Manhattan, Kans.). The grain elevator has a storage capacity of 1400 t (55,000 bu). It has one receiving pit and two bucket elevator legs, each with a maximum feed rate of 81.6 t/h (3,000 bu/h). It is equipped with a pneumatic dust-control system, which includes a 2.74-m diameter low pressure upper cyclone separator and twin 2.24-m diameter low pressure lower cyclone separators (fig. 1). In this research, the system was operated so that the airflow rate through the upper cyclone separators—serving the upper spouting, distributors, and storage bin headspace—was 5.0 m^3/s and the rate through the lower cyclone separators—collecting dust from the ground level area, particularly the elevator boot—was 6.4 m^3/s. These settings were the typical operating conditions for the elevator.

Test Materials and Grain Handling

Part 1: Wheat

The initial study determined the effect of grain lot on the PSD of the grain dust. The test material, Hard Red Winter wheat from the 2005 crop, was purchased from a local elevator on 19-21 July 2005, and stored under aeration in small metal bins for two years. The wheat was then unloaded in the GMPRC research elevator receiving area, moved from the receiving pit by belt conveyor, bucket elevated, and then dropped into the storage bin before testing (fig. 1). It was weighed on the inline weighing scale. There were four lots of wheat. Each of the four lots, with a mean mass of 28.3 t (1000 bu), was transferred each time at an average material flow rate of 52.2 t/h (range: 44.3 to 56.9 t/h). Transfer 1 was a transfer from storage bin 2 (with a volume of approximately 411 m^3 and depth of 26 m) to storage bin 3 (with the same volume and depth as storage bin 2) (fig. 1) on 27 August 2007 with mean temperature (T) and mean relative humidity (RH) of 30.4°C and 56.0%, respectively, during transfer. Transfer 2 was performed from storage bin 3 to storage bin 2 on 28 August 2007 (T = 34.5°C, RH = 36.4%) and 29 August 2007 (T = 22.9°C, RH = 84.2%). The initial grain drop height for each transfer was 26 m. During each of the two transfers for each of the four lots, dust was sampled upstream of the lower and upper collection ducts (fig. 1).

Part 2: Shelled Corn

The second part of the study was conducted to determine the effect of repeated transfers on the PSD of the dust particles. The test material was shelled yellow-dent corn from 2006 crop, air-dried, and also purchased from the same local elevator on 4 April 2007. The shelled corn was weighed while in the truck, unloaded, and bucket elevated into the storage bin before testing. Shelled corn, with a mean mass of 25.3 t (1000 bu), was transferred at an average material flow rate of 56.6 t/h (range: 51.4 to 65.1 t/h). Transfer 1 was a transfer from storage bin 1 (with a volume of approximately 85 m^3 and a depth of 20 m) to storage bin 2. The shelled corn lot was transferred alternately between storage bin 1 and storage bin 2 six times (Transfers 1 to 6) on 24 April 2007 (T = 22.2°C, RH = 76.8%). It was left in storage bin 1 for one week before it was again transferred to storage bin 2 (Transfer 7) on 1 May 2007 (T = 19.7°C, RH = 89.3%). It was left for one more week in storage bin 2 before the final transfer (Transfer 8) on 8 May 2007 (T = 18.2°C, RH = 73.5%). The initial grain drop height to storage bin 1 was 20 m and to storage bin 2 was 26 m. During each of the eight transfers, dust samples were collected upstream of the lower and upper collection ducts (fig. 1).

Dust Sampling

Prior to dust sampling, velocity traverses were conducted inside the lower and upper collection ducts in accordance with US EPA Method 1 (US EPA, 2000) to establish the isokinetic collection velocity in the sampling duct. The mean measured velocities for the lower and upper collection ducts were 17.8 and 19.2 m/s, respectively. The cross-sectional areas of the lower and upper ducts were 0.36 and 0.26 m^2, respectively. Based on the mean velocities and cross-sectional areas, the volumetric flow rates through the lower and upper collection ducts were 6.4 and 5.0 m^3/s, respectively.

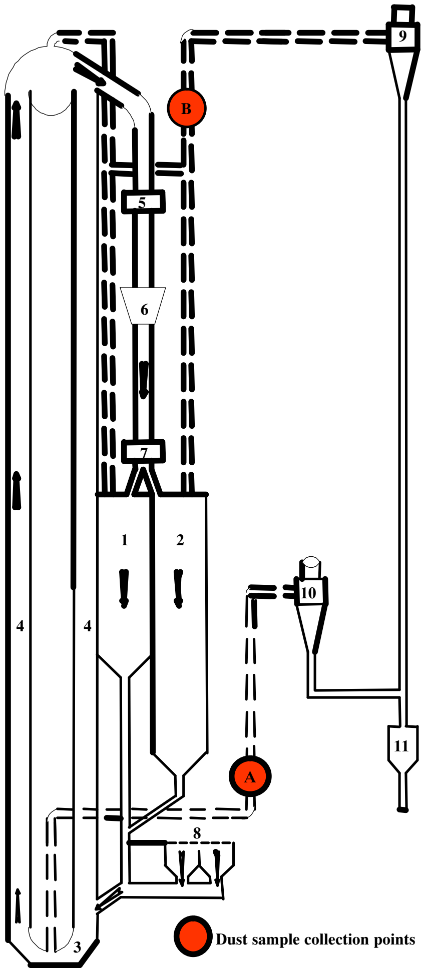

Figure 1. Schematic diagram of the USDA-ARS-GMPRC research elevator showing the flow of the handled grain and location of equipment (not drawn to scale): 1 - storage bin 1; 2 - storage bin 2; 3 - elevator boot; 4 - elevator legs; 5 - diverter-type sampler; 6 - hopper; 7 - distributor; 8 - receiving area; 9 - upper cyclone separators; 10 - lower cyclones separators; 11 - dust bin; A - lower duct sample collection point; and B - upper duct sample collection point.

Dust samples were then collected isokinetically upstream of the cyclones every 5 min during each grain transfer. A total of three samples per grain transfer were collected from each sampling point (fig. 1). Each dust sample was extracted on a 0.20- × 0.25-m glass fiber filter by using a high volume sampling train in accordance with ASTM D4536-96 and US EPA CTM-003 (US EPA, 1989; ASTM Standards, 2000). The high volume sampling train consisted of a 35-mm diameter sampling probe, a 0.20- × 0.25-m filter holder, a differential pressure gauge, and a variable-speed vacuum motor. To achieve isokinetic sampling conditions, the sampling volumetric flow rates for the lower and upper ducts were set at 0.017 and 0.018 m^3/s, respectively.

To minimize the effect of humidity on filter mass, the glass fiber filters were conditioned in a constant humidity chamber (25°C, 50% relative humidity) for at least 24 h prior to weighing both before and after sampling. All filters were weighed on an electronic scale (model PC 440, Mettler Instrument Corp., Hightstown, N.J.) with a sensitivity of 0.001 g. The change in mass before and after sampling represented the mass of dust collected on the filter (m).

From the measured data, the dust mass flow rate, $\dot{m}$ (g/s), was calculated by using:

$$\dot{m} = \frac{m\,Q_c}{t\,Q_s} \tag{1}$$

where Q_c is the volumetric flow rate through the collection duct (m^3/s), t is the sampling time (s), and Q_s is the sampling volumetric flow rate (m^3/s).

The dust mass flow rate was converted to a mass flow rate equivalent, $\dot{m}_e$ (g/t) by using:

$$\dot{m}_e = \frac{\dot{m}}{\dot{M}} \tag{2}$$

where $\dot{M}$ is the grain (i.e., wheat or shelled corn) mass flow rate (t/s).

PARTICLE SIZING

The PSD of the collected dust was measured with a laser diffraction particle size analyzer (model LS 13 320, Beckman Coulter, Inc., Fullerton, Calif.). Laser diffraction particle sizing uses a light source that generates a monochromatic beam, which passes through several optical components that condition it to create an expanded, collimated beam (Beckman-Coulter, Inc., 2006). The beam illuminates the particles in the scattering volume usually in the sample module. The particles then scatter the light, creating unique angular scattering patterns, which are then Fourier transformed into a spatial intensity pattern detected by a multi-element photodetector array. The photocurrent from the detectors is then processed and digitized into an intensity flux pattern. Computer software that utilizes appropriate scattering theories, such as the Mie theory or Fraunhofer theory, then converts the set of flux values into PSD values. The analyzer could measure a particle size range from 0.4 to 2000 μm. Laser diffraction reduces the analysis time to minutes per sample with results tabulated into number, surface area, and volume percentage (Pearson et al., 2007).

The measurement procedure was as follows. First, a quarter of each collection filter was cut and separated for laser diffraction particle sizing. The quarter filter was then washed with isopropyl alcohol to extract the dust on the filter. Isopropyl alcohol was used for the suspension solution to minimize clumping/aggregation of the dust particles. The suspension was placed into plastic centrifuge tubes and centrifuged for 5 min at 4000-rpm setting inside the Durafuge (model Precision Durafuge 300, Thermo-Fisher Scientific, Inc., Waltham, Mass.). The excess isopropyl alcohol was discarded, and the dust suspension was collected into one 50-mL plastic centrifuge tube. The dust suspension was agitated on a vortex mixer (model Sybron Thermolyne Maxi Mix, Thermolyne Corp., Dubuque, Iowa) just prior to analysis.

A subsample consisting of drops of the dust suspension was added into the wet module of the laser diffraction analyzer until the manufacturer-recommended obscuration value of between 8% and 12% was reached. Sonication of the subsample was done for 90 s just prior to analysis to minimize aggregation of the subsample. The instrument duplicated the 60-s analysis time for each subsample (Pearson et al., 2007). There were at least two subsamples analyzed for every sample.

Particle size distribution and statistics data on the dust samples were extracted from the instrument's computer software. The geometric mean diameter (GMD) and geometric standard deviation (GSD) of the equivalent sphere particles were determined from each of the data set.

The equivalent sphere diameter (d_p) of the dust particles from laser diffraction was converted into equivalent aerodynamic diameter (d_a) by using:

$$d_a = d_p \sqrt{\frac{\rho_p}{\rho_0}} \tag{3}$$

where ρ_p is the particle density and ρ_0 is the unit density (i.e., 1.0 g/cm^3). A multipycnometer (model MVP-1, Quantachrome Corp., Syosset, N.Y.) was used to measure ρ_p of the wheat and shelled corn dust from at least three replicates. The measured ρ_p values for wheat and shelled corn dust were 1.48 g/cm^3 (SD = 0.022 g/cm^3) and 1.51 g/cm^3 (SD = 0.014 g/cm^3), respectively.

The percentages of PM-2.5, PM-10, and PM-4 were interpolated from the cumulative volume percentages of the dust PSD based on their aerodynamic diameters.

DATA ANALYSIS

The four wheat grain lots were the experimental units in the first part of the study. The class variables were the four grain lots (Lots 1 to 4), two transfers (T1, T2), and two ducts (upper, lower). The null hypothesis was there were no mean differences in GMD, GSD, and mass flow rates among the four grain lots, between the two transfers and between the two ducts. Analysis of Variance (ANOVA) and Bonferroni Multiple Comparison Test in SAS (version 9.1.3, SAS Institute Inc., Cary, N.C.) were used for analysis at the 5% level of significance. Differences between grain lots were not expected so we used Bonferroni because of its strict requirements prior to rejecting the null hypotheses, which minimizes Type I errors. The differences in results between the lower and upper ducts were compared to determine the necessity of sampling from both ducts.

The shelled corn lot was the experimental unit in the second part of the study. The eight transfers (T1 to T8) and the two ducts (upper, lower) were the class variables. The null hypothesis was there were no mean differences in the parameters among the eight transfers and between the two ducts. Similar to the first part of the study, data were analyzed by using ANOVA and Bonferroni.

Comparisons of results between wheat and shelled corn dust were also performed by using ANOVA and Bonferroni. The differential volume percentages of the PSD of wheat and shelled corn dust were analyzed by using the Kruskal-Wallis test, a non-parametric method for testing equality of sample medians among groups (Hollander and Wolfe, 1973; SAS, 1990). Combinations of variables were also analyzed by using ANOVA and Bonferroni (table 3).

RESULTS AND DISCUSSION

GMS, GSD, and mass flow rate values were analyzed on the basis of the combination of statistical variables in table 3. Results of data analysis for wheat dust were narrowed down to differences among the four grain lots, between the two transfers and between the two ducts because the results of the variable combinations closely followed general trends. For corn dust, presentation of results followed that indicated in table 3.

MASS FLOW RATE

The dust mass flow rates of wheat did not differ significantly ($p > 0.05$) among the four grain lots or between the two transfers ($p > 0.05$). The dust mass flow rate for the upper duct (39.4 g/t) was significantly greater ($p < 0.05$) than that for the lower duct (25.2 g/t) (table 4). The total dust mass flow rate for wheat (64.6 g/t) collected upstream of the cyclone separators was within the range of published emission factors for grain receiving (8.30 to 90.0 g/t; table 1).

Similar to wheat, for shelled corn the dust mass flow rates were not significantly different ($p > 0.05$) among the eight transfers but differed significantly ($p < 0.05$) between the two ducts. Again, the dust mass flow rate for the upper duct (119.6 g/t) was significantly greater than that of the lower duct (65.5 g/t) (table 4). The total dust mass flow rate for shelled corn (185.1 g/t) collected upstream of the cyclone separators was greater than the published emission factors for grain receiving (8.30 to 90.0 g/t) but within the emission factors for grain drying (110 to 1500 g/t; table 1). For both wheat and shelled corn in the elevator in this study, more dust was generated and then collected by the pneumatic dust control system from the upper duct (elevator head and the storage bin headspace) than from the lower duct (elevator boot).

Of the two grain types, shelled corn (185.1 g/t) had significantly greater dust generated, as given by the mass flow rates, than wheat (64.6 g/t), likely because of the tendency of corn to generate more dust than wheat during handling (Martin and Sauer, 1976; Martin and Lai, 1978; Parnell et al., 1986). Fiscus et al. (1971) found that corn had the highest breakage during various handling techniques compared with wheat and soybean because of the structurally weak kernel of corn that fragmentized into random particles sizes during the breakage process. Wheat, on the other hand, had the lowest breakage and generated dust (Martin et al. 1985) and small kernel particles mainly by abrasion (Fiscus et al., 1971). The values of dust mass flow rates for both wheat and shelled corn in this study were relatively high compared with other published values because both collection points were upstream of the cyclone separators.

PARTICLE SIZE DISTRIBUTION AND SIZE FRACTIONS

Wheat – Effect of Grain Lot

In general, the GMD and GSD values were not significantly different ($p > 0.05$) among the four grain lots and between the two transfers (table 5). The GMD values from the upper duct (10.5 to 13.7 μm) were significantly smaller ($p < 0.05$) than those from the lower duct (12.9 to 16.9 μm). However, the GSD values from the upper duct (2.60 to 2.98) were not

Table 4. Mean dust mass flow rates for wheat and shelled corn collected from the upper and lower ducts, upstream of the cyclones.[a]

	Mean Dust Mass Flow Rate (SD)			
Source	(g/s)		(g/t of grain handled)	
Wheat				
Upper duct (storage bin and elevator head)	0.571 A a	(0.113)	39.4 A a	(7.78)
Lower duct (elevator boot)	0.365 B b	(0.159)	25.2 B b	(10.9)
Total	0.937	(0.271)	64.6	(18.7)
Shelled corn				
Upper duct (storage bin and elevator head)	1.88 A c	(0.270)	119.6 A c	(17.2)
Lower duct (elevator boot)	1.03 B d	(0.169)	65.5 B d	(10.8)
Total	2.91	(0.440)	185.1	(28.0)

[a] For the same type of grain, mean values with the same upper case letters within a column are not significantly different at the 5% level of significance in Bonferroni. For comparison among both location and grain, mean values with the same lower case letters within a column are not significantly different at the 5% level of significance in Bonferroni. Values in parentheses represent standard deviation (SD).

Table 3. Combination of variables for the wheat and shelled corn dust data analysis for GMD, GSD, and mass flow rate.

Wheat Dust

Variable	Grain Lot (Lots 1 to 4)	Transfer (T1, T2)	Duct (Upper, Lower)
Grain Lot (lots 1 to 4)	–	Compare ducts	Compare transfers
Transfer (T1, T2)	Compare ducts	–	Compare grain lots
Duct (upper, lower)	Compare transfers	Compare grain lots	–

Shelled Corn Dust

Variable	Transfer (T1 to T8)	Duct (Upper, Lower)
Transfer (T1 to T8)	–	Compare ducts within each transfer
Duct (upper, lower)	Compare transfers within each duct	–

Table 5. Geometric mean diameter (GMD) and geometric standard deviation (GSD) of wheat dust collected from the upper and lower ducts, upstream of the cyclones.[a]

	GMD, μm (SD, μm)				GSD (SD)			
Transfer (T) - Grain Lot (W)	Upper Duct		Lower Duct		Upper Duct		Lower Duct	
T1 - W1	12.6 a	(3.63)	12.9 b	(1.69)	2.75 a	(0.283)	2.76 a	(0.264)
T1 - W2	10.5 a	(2.03)	13.6 bc	(1.26)	2.60 a	(0.350)	2.74 a	(0.209)
T1 - W3	12.8 a	(2.65)	14.4 bc	(0.323)	2.94 a	(0.321)	2.84 a	(0.077)
T1 - W4	11.7 a	(1.56)	15.7 cd	(2.03)	2.75 a	(0.243)	2.87 a	(0.132)
T2 - W1	12.8 a	(1.76)	13.9 b	(1.76)	2.98 a	(0.333)	2.79 a	(0.145)
T2 - W2	11.8 a	(1.35)	15.5 b	(1.87)	2.83 a	(0.289)	2.93 ab	(0.122)
T2 - W3	12.5 a	(0.676)	16.0 b	(0.825)	2.80 a	(0.100)	2.99 a	(0.128)
T2 - W4	13.7 a	(0.933)	16.9 bd	(2.70)	2.86 a	(0.138)	2.99 a	(0.300)
Mean (SD)	12.3	(0.975)	14.9	(1.37)	2.81	(0.120)	2.86	(0.097)

[a] Means with the same letter are not significantly different at the 5% level of significance in Bonferroni. Values in parentheses represent standard deviations (SD).

significantly different ($p > 0.05$) than those from the lower duct (2.74 to 2.99).

The mean GMD from the upper duct (12.3 μm), which had a corresponding mass median diameter (MMD) of 12.2 μm, was smaller than the MMD reported by Parnell et al. (1986) (i.e., 13.4 μm for dust fraction of wheat < 100 μm) and Martin and Lai (1978) (i.e., 13 μm for residual wheat dust). The mean GMD from the lower duct (14.9 μm), which had the same MMD value (14.9 μm), was greater than both of these published MMD values.

The mean GSD values from the upper (2.81) and lower (2.86) ducts were greater than the GSD from Parnell et al. (1986), which was 2.08. This is characteristic of wheat dust PSD from a wider range of particle sizes than the wheat dust of Parnell et al. (1986), which was limited to the dust fraction < 100 μm. These differences in the GMD and GSD could possibly be due to variation in grain properties, grain elevator operation and characteristics, and sampling methods and measurement.

The dust in this study would also be different from that of Parnell et al. (1986) because of the disparity in the dust generation mechanisms. The dust from this study came mainly from the elevator boot, elevator head, and storage bin headspace, whereas Parnell et al.'s (1986) dust was taken from all the operations in the terminal elevators. Although similar sets of equipment were also probably involved, the drop height, speed of impact, and other mechanisms were likely quite different. The sampling methods were also different. Dust in the Parnell et al. (1986) study was collected from baghouse filters, whereas the dust in this study was collected by a high volume sampler upstream of the cyclone separators.

The mechanisms of dust generation from the upper duct were different than those from the lower duct. There were two sources for the dust generated and collected in the upper duct, the elevator head and filling of the storage bin. Dust generated for the lower duct was from a single source, the elevator boot. The various sources of generated dust have disparate mechanisms for damaging the grain and thus might be expected to generate dust with diverse characteristics. Apparently, these disparate mechanisms for dust generation led to the differences in dust particle sizes from the upper and lower ducts.

Figure 2 shows a representative plot of the cumulative and differential volume percentages of PSD of wheat dust. The Kruskal-Wallis test showed that the PSD among the four grain lots from upper and lower ducts and from the two transfers were not significantly different ($p > 0.05$), which is in agreement with the results of GMD and GSD. It appears that differences in grain lots did not affect the PSD of the wheat dust.

With significant difference in GMD (or PSD) between the upper and lower ducts, there were corresponding differences in the three size fractions of interest (i.e., PM-10, PM-2.5, PM-4). The percentage of PM-10 of the dust sample collected upstream of the upper duct (37.3%) was significantly greater ($p < 0.05$) than that of the sample from the lower duct (27.8%), which was consistent with the findings on mass flow rate. The mean percentage of PM-10 for wheat dust was 33.6% (table 6). This percentage of PM-10 was greater than the values reported by Martin (1981) for dust < 10 μm from cyclones (9%) and baghouses (20%) (mean for corn, wheat, sorghum, and soybean dusts) and was smaller than that from the residual wheat dust ≤ 10 μm (45%) obtained by Martin and Lai (1978). This value was also slightly greater than the average percentage of PM-10 emissions (30%) from elevators primarily handling wheat (Midwest Research Institute, 1998). The wheat dust generated, as given by the mass flow rate equivalent of mean PM-10 (21.7 g/t of wheat handled), was comparable to the published emission value for grain receiving (0.60 to 29.5 g/t) (table 1).

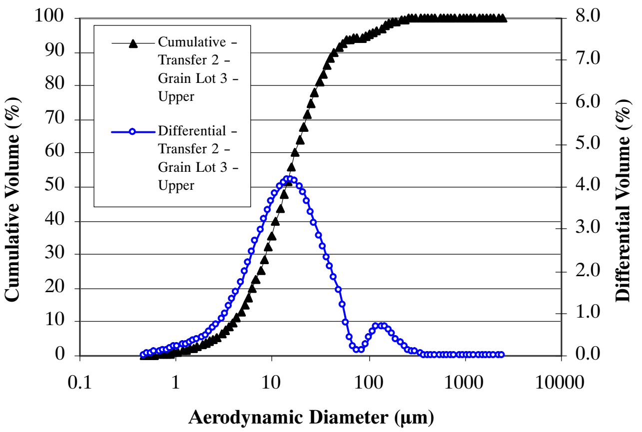

Figure 2. Representative plot of mean cumulative and differential volume percentages for the particle size distribution of wheat dust.

The percentage of PM-2.5 for the samples collected from the upper duct (5.42%) was not significantly different ($p > 0.05$) than that from the lower duct (4.73%) (table 6). The mean percentage of PM-2.5 (3.33 g/t of wheat handled) was also within the range of published emission values for grain receiving (0.65 to 5.0 g/t) (table 1).

The percentage of PM-4 for the samples collected from the upper duct (10.7%) was significantly greater ($p < 0.05$) than that from the lower duct (8.0%). The mean of PM-4 was 9.65% (equivalent to 6.24 g/t of wheat handled) (table 6). Literature contained no data with which to compare the percentage of PM-4 for wheat dust.

Shelled Corn – Effect of Repeated Transfers

The eight transfers did not differ significantly ($p > 0.05$) in GMD and GSD values (table 7). The GMD values from the upper duct (10.0 to 11.1 µm) were significantly less ($p < 0.05$) than the values from the lower duct (11.2 to 14.4 µm) because of the smaller particles generated and collected by the pneumatic dust collection system from the elevator head and storage bin headspace. The GSD values from the upper duct (2.27 to 2.36) were also significantly different ($p < 0.05$) from those of the lower duct (2.31 to 2.77).

The mean GMD from the upper duct (10.5 µm), with a corresponding MMD of 12.2 µm, was smaller than the MMD obtained by Parnell et al. (1986) (i.e., 13.2 µm for dust fraction of corn < 100 µm). The mean GMD from the lower duct (12.1 µm), with a MMD of 13.5 µm, was greater than the MMD of Parnell et al. (1986) (i.e., 13.2 µm for dust fraction of corn < 100 µm). The mean GSD values from the upper (2.32) and lower (2.44) ducts were also greater than the GSD from Parnell et al. (1986), which was 1.80. The differences in the GMD and GSD between the upper and lower ducts and the differences in MMD of the shelled corn dust in this study and that of Parnell et al. (1986) are likely due to the same factors as explained previously for wheat—differences in grain properties, grain elevator operation and characteristics, and sampling methods and measurement.

Figure 3 shows a representative plot of the cumulative and differential volume percentage of PSD of shelled corn dust. The Kruskal-Wallis test showed that the PSD among the eight transfers from the upper and lower ducts were not significantly different ($p > 0.05$), which is in agreement with the results of GMD and GSD. Apparently, repeated transfers of corn did not affect the PSD of the generated dust.

Similar to wheat, difference in GMD or PSD between the upper and the lower ducts resulted in a significant difference in PM-10, PM-2.5, and PM-4 in terms of percentages or flow rates. The percentage of PM-10 from the upper duct (30.8%) was significantly greater ($p < 0.05$) than that from the lower duct (25.5%) (table 6). The resulting mean percentage of PM-10 was 28.9%, slightly greater than that reported for

Table 6. Percentage of particulate matter of the total dust (% PM) and its mass flow rate equivalent (MFRE).[a]

Aero-dynamic Diameter (µm)	Lower Duct				Upper Duct				Mean for Lower and Upper Ducts			
	% PM (SD)		MFRE (SD), g/t of grain handled		% PM (SD)		MFRE (SD), g/t of grain handled		Mean % PM		Mean MFRE, g/t of grain handled	
Wheat Dust												
2.5	4.73 A a	(0.886)	1.19	(0.223)	5.42 A a	(0.586)	2.14	(0.231)	5.15 a	(0.703)	3.33	(0.454)
4	8.00 A b	(0.888)	2.02	(0.224)	10.7 B b	(0.897)	4.22	(0.353)	9.65 b	(0.893)	6.24	(0.577)
10	27.8 A c	(1.61)	7.01	(0.406)	37.3 B c	(3.25)	14.7	(1.28)	33.6 c	(2.61)	21.7	(1.69)
Corn Dust												
2.5	7.21 A d	(0.275)	4.72	(0.180)	7.59 B d	(0.240)	9.08	(0.287)	7.46 d	(0.252)	13.8	(0.467)
4	9.57 A b	(0.257)	6.27	(0.168)	10.2 B e	(0.287)	12.2	(0.343)	9.99 b	(0.277)	18.5	(0.512)
10	25.5 A e	(1.60)	16.7	(1.05)	30.8 B f	(1.93)	36.8	(2.30)	28.9 e	(1.81)	53.5	(3.35)

[a] For the same type of grain and aerodynamic diameter, mean values for upper and lower ducts with the same upper case letters within a row are not significantly different at the 5% level of significance in Bonferroni. For comparison among both location and grain, mean values with the same lower case letters within a column are not significantly different at the 5% level of significance in Bonferroni. Values in parentheses represent standard deviation (SD).

Table 7. Geometric mean diameter (GMD) and geometric standard deviation (GSD) of shelled corn dust collected from the upper and lower ducts, upstream of the cyclones.[a]

Transfer (T)	GMD, µm (SD, µm)				GSD (SD)			
	Upper Duct		Lower Duct		Upper Duct		Lower Duct	
T1	10.3 a	(0.157)	14.4 b	(4.70)	2.35 a	(0.084)	2.77 b	(0.774)
T2	10.7 a	(0.412)	12.1 b	(0.883)	2.34 a	(0.047)	2.52 b	(0.275)
T3	10.7 a	(0.404)	11.9 b	(0.496)	2.36 a	(0.055)	2.37 b	(0.010)
T4	10.4 a	(0.311)	11.2 b	(0.743)	2.31 a	(0.054)	2.31 b	(0.036)
T5	11.1 a	(0.580)	11.9 b	(0.606)	2.31 a	(0.024)	2.36 b	(0.036)
T6	11.0 a	(0.178)	11.7 b	(0.232)	2.33 a	(0.048)	2.35 b	(0.010)
T7	10.1 a	(0.491)	12.3 b	(1.59)	2.32 a	(0.038)	2.48 b	(0.201)
T8	10.0 a	(0.484)	11.2 b	(0.720)	2.27 a	(0.024)	2.33 b	(0.103)
Mean (SD)	10.5	(0.393)	12.1	(1.01)	2.32	(0.028)	2.44	(0.153)

[a] Means with the same letter are not significantly different at the 5% level of significance in Bonferroni. Values in parentheses represent standard deviations (SD).

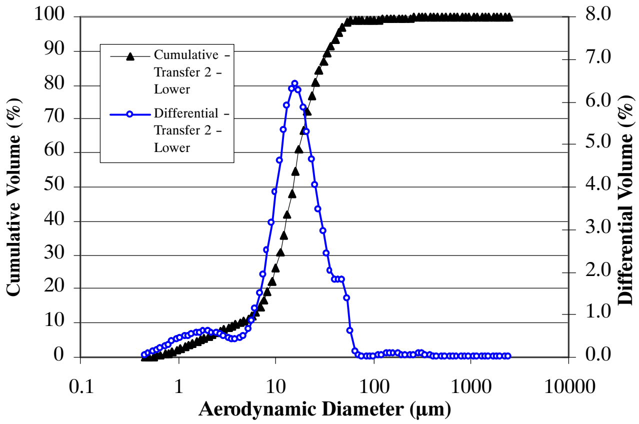

Figure 3. Representative plot of mean cumulative and differential volume percentages for the particle size distribution of shelled corn dust.

elevators primarily handling corn and soybean (< 20%) (Midwest Research Institute, 1998). This percentage of PM-10 was greater than the values reported by Martin (1981) from cyclones (9%) and from baghouses (20%) (mean for corn, wheat, sorghum, and soybean dusts), Lai et al. (1984) and Baker et al. (1986) (5% to 12% for corn, wheat, sorghum, and corn starch) and smaller than those from the residual corn dust ≤ 10 μm (33%) obtained by Martin and Lai (1978). The corn dust generated, as given by the mass flow rate equivalent of mean PM-10 (53.5 g/t of shelled corn handled), was greater than the published PM-10 for grain receiving (0.60 to 29.5 g/t) and within the range of published PM-10 for grain drying (27.5 to 375 g/t) (table 1).

The percentage of PM-2.5 from the upper duct (7.59%) was significantly greater ($p < 0.05$) than that from the lower duct (7.21%). The weighted mean PM-2.5 in this study (7.46%) (table 6) was greater than the value reported by Baker et al. (1986) (0.2% to 1.0%) for pneumatic conveying of corn (table 2). The difference in values may be explained by the use of velocity compensators to reduced grain damage and dust generation in a pneumatic handling system where grain flow rates and conveying distances were drastically reduced (Baker et al., 1986). The corn dust generated, as given by mass flow rate equivalent (13.8 g/t of shelled corn handled), was greater than the published PM-2.5 for grain receiving (0.65 to 5.0 g/t) and within the range of published PM-2.5 for grain drying (4.7 to 65.0 g/t) (table 1). This implies that without the pneumatic dust collection system, the PM-2.5 of the elevator handling corn would be similar to that of grain drying.

The percentage of PM-4 from the lower duct (9.57%) was significantly smaller ($p < 0.05$) than that from the upper duct (10.2%) (table 6). The weighted mean PM-4 was 9.99% (equivalent to 18.5 g/t of shelled corn handled). Literature contained no data with which to compare the percentage of PM-4 from corn dust.

Comparison of Wheat and Shelled Corn – Effect of Grain Type

The GMD values of wheat dust (10.5 to 16.9 μm) were significantly greater ($p < 0.05$) than those of shelled corn dust (10.0 to 14.4 μm). The same was true when comparing the GSD values of wheat dust (2.60 to 2.99) with those of corn (2.27 to 2.77). This implies that handling shelled corn generated dust particles that were generally smaller in diameter than those from wheat.

Comparisons of GMD and GSD values within each duct (upper vs. lower) showed that wheat and corn dust were significantly different ($p < 0.05$). However, GMD and GSD values of wheat dust were not significantly different ($p > 0.05$) from that of shelled corn dust within Transfer 1 but significantly differ ($p < 0.05$) within Transfer 2. This may be due to inherent variability between the transfers and the test materials.

It must be emphasized that the dust collected from the ducts in this study was upstream of the cyclone collectors; thus, most of it was not emitted to the atmosphere. The relationship of this dust (from upstream of the cyclone) and the dust that would be emitted without a pneumatic dust collection system is not known. However, it could be speculated that the measurement results for dust taken upstream of the cyclone (or any similar control devices) would likely be greater than those taken from sources with no pneumatic dust control system. The relative difference would depend on the air velocities and design of the pneumatic dust control system among others. Establishing the relationship between the two measurements could be considered for future work. Another issue for future work includes the effect of air velocities or volumetric flow rate on the measurements.

CONCLUSIONS

The PSD of grain dust generated during handling in a bucket elevator system was characterized by using a laser diffraction analyzer. The percentages of PM-2.5 and PM-10 (which are regulatory concerns), PM-4 (a health concern), and the mass of generated dust (mass flow rate equivalent) were measured. The effect of different grain lots and repeated transfers on the dust size distribution were studied by using wheat and shelled corn dusts, respectively. The effect of grain types on particle size distribution was also studied. The dust samples were collected on glass fiber filters with high volume samplers from the lower and upper ducts upstream of the cyclones. The following conclusions were drawn from the research:

- Shelled corn produced significantly smaller dust particles, and a greater proportion of small particles, than wheat. GMD of shelled corn dust ranged from 10.0 to 14.4 μm; GSD ranged from 2.27 to 2.77. For wheat, GMD ranged from 10.5 to 16.9 μm, and GSD ranged from 2.60 to 2.99. The percentage of PM-2.5, PM-4, and PM-10 generated during the transfer operation were 7.46%, 9.99%, and 28.9%, respectively, of total shelled corn dust and 5.15%, 9.65%, and 33.6%, respectively, of total wheat dust.
- Handling shelled corn generated more than twice as much total dust than handling wheat (185 g/t of corn handled vs. 64.6 g/t of wheat handled).
- For both wheat and shelled corn, at an average grain flow rate of 54.4 t/h, the size distribution of dust from the upper and lower ducts showed similar trends among grain lots and repeated transfers but differed between the two grain types and also between the two ducts.

Overall, the corn and wheat differed significantly in the dust size distribution and the rate of total dust generated and there were significant differences between the lower and upper ducts, confirming the necessity of sampling from both ducts.

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