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Measurement of Air Entrainment and Dust Emission during Shelled Corn Receiving Operations with Simulated Hopper Bottom Grain Trailers

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Abstract. *Dust emissions from grain elevator operations can be a safety and health risk and a nuisance. Dust emission and air entrainment data are needed for designing adequate and effective control methods. This study measured the dust emitted and air entrained during corn receiving operations at an elevator operated by the USDA Grain Marketing and Production Research Center, Manhattan, Kans. Shelled corn (maize) was unloaded from a storage bin, representing a hopper bottom truck, to the dump pit at rates of 17 to 118 kg/s. The resulting airflow rates and dust emissions were measured with propeller anemometers and high volume samplers, respectively. Both the amount of air entrained per unit volume of grain (specific air entrainment) and dust emission rate expressed as g of dust per unit mass of grain decreased with increasing grain flow rate. The highest specific air entrainment was 2.07* m^3/m^3 *at a grain flow rate of 17 kg/s while the lowest was 0.27* m^3/m^3 *at a grain flow rate of 114 kg/s. The highest dust emission rate was 14.6 g/tonne at a grain flow rate of 17 kg/s while the lowest was 8.3 g/tonne at a grain flow rate of 118 kg/s.*

Keywords. air entrainment, dust emission, grain dust, dust control method, shelled corn, BCFM

Introduction[1]

Dust is generated by the abrasion and attrition of the grain kernels whenever the grain mass is mechanically transferred or conveyed. The dust generated may affect the health of the workers and cause air pollution and contribute to dust explosions. The amount of dust emitted during unloading/receiving operations depends on several factors, including grain flow rate, type of grain, quality or grade of grain, moisture content of the grain, degree of enclosure in the receiving area, and effectiveness of dust capture/collection systems. Grain receiving from trucks, considered one of the dustiest operations in a grain elevator, generates dust-laden air as grain is dumped from a truck and falls into the receiving pit. Dust-laden air results from the displacement of air from the pit and the aspiration or entrainment of air caused by falling grain (MRI, 1998). Many grain facilities, except for relatively small grain elevators, use dust capture/collection systems on the receiving pits to control dust emission (Wallace, 2000). These dust capture/collection systems should be designed to extract a volume of air that matches the air entrained and that displaced by the grain mass. Previous studies on air entrainment have concentrated on powders and other bulk materials (Hemeon, 1963; Dennis and Bubenick, 1983; Cooper and Arnold, 1995). Limited research has been conducted on the air entrainment during grain receiving operations.

Information is available on total particulate matter emissions from grain handling and processing facilities; however, data on the particle size distribution of these emissions and on the fraction of emissions that might be a health hazard are limited (Wallace, 2000). Kenkel and Noyes (1995) measured the amount of grain dust generated when receiving wheat at a country elevator; receiving grain from a straight truck emitted 19.4 g/tonne of airborne dust while receiving from a hopper bottom truck emitted 9.5 g/tonne. Shaw et al. (1998) measured dust emission rates for corn receiving and feed loading operations at feed mills associated with cattle feed yards. In that study, the average dust emission rate for corn receiving measured over 20 trucks in three feed mills was 8.5 g/tonne (S.D.=9.0 g/tonne). EPA considered particulate matter less than 10 μm in diameter (PM-10) as the basis for determining major sources of particulate matter (PM) emission (Wegman, 1995). Emission factors for grain elevators were based on total PM and PM-10; for grain receiving operations, PM emission ranged from 16 to 29.5 g/tonne; 20 to 30% of which are PM-10 (EPA, 1998).

The objective of this study was to measure the amount of dust emitted and air entrained during simulated corn receiving operations at a grain elevator as affected by the grain flow rate.

Methodology

All experiments were conducted at an elevator operated by the USDA Grain Marketing and Production Research Center (GMPRC), Manhattan, Kans. The elevator had a storage capacity of 1938 m^3; it had one receiving/dump pit and two bucket elevator legs. The dump pit in the receiving area measured approximately 3.66 m x 3.66 m and was covered by eight 0.45 m x 3.6 m steel bar grates. A dust control baffle system was located underneath the metal grates (Kenkel and Noyes, 1995). Two suction vents, which were part of the existing pneumatic dust

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[1] This article reports the results of the research only. Mention of a propriety product or company names is for clarity of the presentation and does not constitute an endorsement or recommendation by the authors or USDA.

collection system, were located inside the dump pit hopper. The dump pit hopper was 3.84 m wide, 4.88 m long and 2.91 m deep and could hold up to 28 m^3 (800 bu) of grain.

Air Entrainment

Experimental set-up

Air entrainment during grain receiving was measured using the apparatus shown in figure 1. Preliminary tests were first conducted to develop a suitable experimental set-up for air entrainment measurement. These tests involved dumping shelled corn through an opening in a plastic covered-dump pit with air exhausted through two 25.4-cm round ducts. The dust control suction vents were also sealed. As shown in figure 2, displaced and entrained air escaped through the spaces between the grain kernels as the grain spreads out over the metal grate leaving no obvious way to measure the entrained air. For those tests, mean airflow rate measured at the exhaust ducts (5.6 m^3/min) were less than the volumetric grain flow rate (8.9 m^3/min), indicating that a significant amount of air escaped from the grain as it spreads.

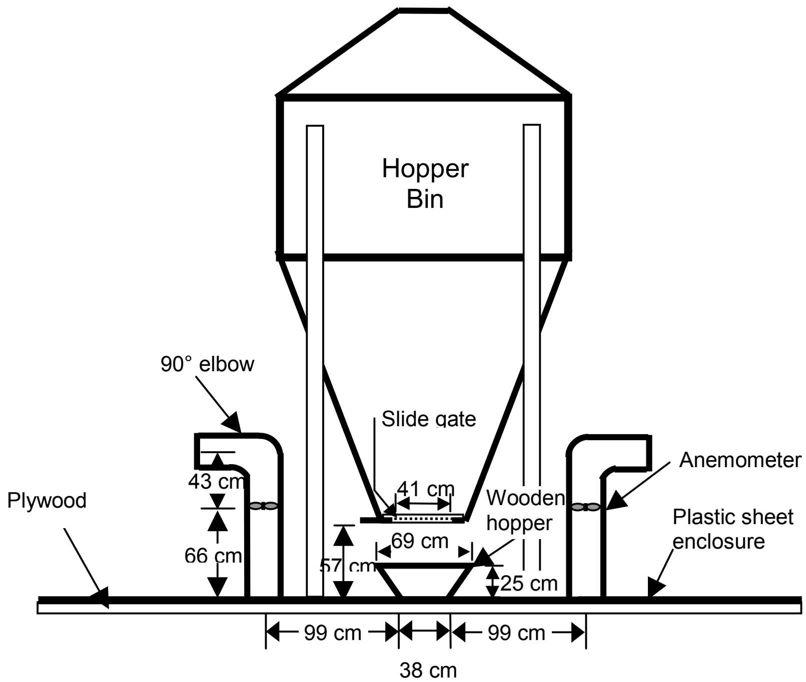


Figure 1. Schematic diagram of air entrainment set-up (not drawn to scale).

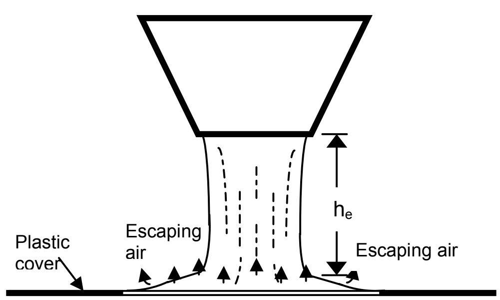


Figure 2. Preliminary set-up the without wooden hopper

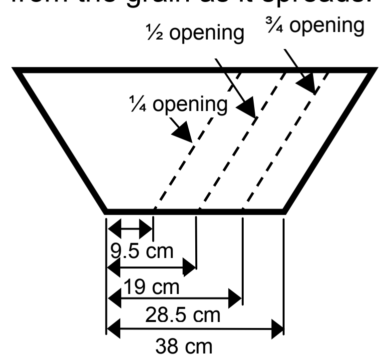
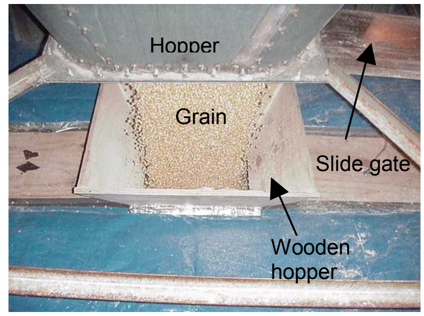
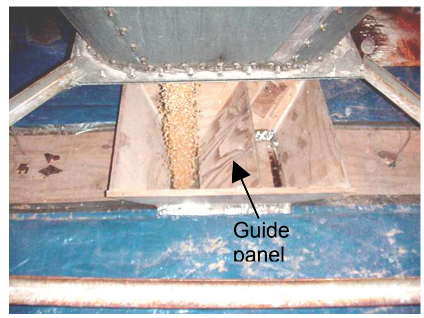


Figure 3. Wooden hopper showing the position of the guide panel at different slide gate openings.

To improve the airflow measurements from the dump pit, one of the metal grates was replaced with 1.9-cm-thick plywood sheet. The pivoting panels of the dust control baffle assembly were also removed. A plastic sheet covered the dump pit perimeter and was sealed with duct tape. The existing dust control suction vents were also sealed. A wooden hopper (figure 3) was placed on the center of the dump pit to avoid grain spillage and allow the grain to flow smoothly. Additional guide panels were placed on the hopper to prevent the escape of air at lower grain flow rates. Figure 4 shows the flow of grain as it passes from the slide gate to the wooden hopper. Unlike the grain flow with the metal grate in place, the grain flowed vertically through the slide gate and passed through the wooden hopper without the build up of grain. The major difference between the preliminary set-up and the new set-up is the effective drop height (h_e), which is the distance from the slide gate to the top of the grain build-up (figure 2). Since there was no build up of grain, the effective drop height without the metal grate is the same as the actual drop height. However, the removal of the grate should have minimal effect on air entrainment. A very small amount of air can be induced by the grain during retarded flow with an almost flat slope, which is the case when the grain spreads on the grate. Observations during the preliminary tests revealed that dust-laden air was forced out of the pit through part of the grain spreading over the grate, as opposed to any indication of air entrainment there.



(a)



(b)

Figure 4. Grain flow through the wooden hopper at (a) full flow and (b) partial flow (1/4 slide gate opening).

Two 22-cm diameter propeller anemometers (Model 27106, R. M. Young Co., Transverse City, Mich.) were mounted in two 25.4-cm diameter round ducts to measure airflow rates induced by the falling grain. The propeller rotation was converted into DC voltage by the tachometer-generator; this voltage was linearly correlated to air speed or airflow rate. A datalogger (21X Micrologger, Campbell Scientific, Inc., North Logan, Utah) monitored and recorded the voltage output from the anemometer. To establish the relationship between the volumetric airflow rate and voltage output, the anemometers were calibrated in a fan test chamber, which was designed and built according to AMCA standard 210-85 (AMCA, 1985).

A hopper-bottom truck was simulated by using a round steel hopper bin with a capacity of approximately 5 tonnes of shelled corn (approximately 200 bushels). A slide gate at the bottom of the bin allowed variation in the grain flow rate. Four slide gate openings were selected, corresponding to four different grain flow rates: full opening at 114 kg/s (8.9 m^3/min; 15,100 bu/h), three-fourth opening at 87 kg/s (6.8 m^3/min; 11,200 bu/h), one-half opening at 47 kg/s (3.7 m^3/min; 6,200 bu/hr) and one-fourth opening at 17 kg/s (1.3 m^3/min; 2,300 bu/hr). Each grain flow rate test was replicated three times.

The dump pit construction made it difficult to achieve a completely airtight system. To quantify the air leakage through the system, an axial flow fan was installed on one side of the covered dump pit where one of the anemometers was originally located. One propeller anemometer was placed at the fan inlet to measure the inlet airflow rate. The other anemometer was positioned at the other side of the dump pit to measure exhaust airflow rate. The fan was operated with flow rates ranging from 1.8 to 14.9 m^3/min. The leakage rate, which was the difference between the inlet and exhaust airflow rates, ranged from 1.1 to 4.0 m^3/min. Regression analysis was used to estimate the leakage rate in terms of the exhaust airflow rate.

Test Procedure

All the doors at the truck dump pit area were closed to minimize the effect of ambient wind on airflow measurements. Corn was first loaded into the hopper bin from the overhead holding bin through a metal chute. The volume of corn was estimated by taking the product of the cross sectional area of the storage bin (6.9 m^2) and the difference between initial height and final height of the grain level in the bin. The corn was unloaded by opening the hopper bin slide gate for a predetermined time (0.6 to 4.0 min). The average grain mass flow rate ($\dot{m}_g$) was computed as:

$$\dot{m}_g = V\rho_b / t \qquad (1)$$

where:

V= bulk volume of corn, m^3 (loose corn and air void space)

ρ_b= bulk density of corn, kg/ m^3

t = unloading time, sec

Additional 90° elbows were connected to the airflow measurement ducts above the anemometers (figure 1) to prevent the air leaking through the doors from influencing the airflow measurements. The volumetric airflow rates coming out of the ducts were measured by the datalogger at 0.5 sec intervals during the each test. To document air density and moisture conditions during each test, temperature and relative humidity were measured with an aspirated psychrometer, and atmospheric pressure was determined using a barometer. Static pressure under the plastic enclosure was also measured for each grain flow rate with an inclined manometer. Static pressure only ranged from 2.5 to 7.5 Pa (0.01 to 0.03 in H_2O) indicating that the enclosure had minimal restraint on the flow of air through the ducts.

The amount of entrained air was expressed in terms of specific air entrainment, SE (m^3 of air/m^3 of grain) and was computed as:

$$SE = (Q_{exhaust} + Q_{leak} - Q_{grain}) / (Q_{grain}) \qquad (2)$$

where:

$Q_{exhaust}$= average volumetric air flow rate from the ducts, m^3/min

Q_{leak}= estimated air leakage rate, m^3/min

Q_{grain} is equal to the total volumetric grain flow rate, which was computed as the bulk volume of corn, V over the unloading time, t. The outflow of grain from the pit was zero since the dump pit conveyor was not operating during the tests.

Dust emission

Experimental set-up

For dust emission rate measurement, the dump pit perimeter was enclosed using a wooden frame and plastic sheet (figure 5). The enclosure, with a cross sectional area of 1.87 m^2 (3.54 m wide x 0.53 m high) served as a channel for dust-laden air. All the doors in the truck dump pit area were closed during the test. In order to simulate and control the effect of ambient wind, four box-type fans, located on one end of the enclosure were operated to blow air across the dump pit area. Three high volume (HiVol) samplers with 20 x 25 cm glass fiber filters (Type A/E, Pall Life Sciences, Ann Arbor, Mich.) were placed on the other end of the enclosure to collect samples of the total suspended particulates (TSP). The sampling flow rates of HiVols 1 and 3

(Model 500, Bendix Corp., Lewisburg, W. Va.), which had 10 x 20 cm sampling probes, were indicated by the pressure drop measured by an inclined manometer at the sampler exhaust. The sampling flow rate for HiVol 2, which had a 6 x 20 cm probe, was measured by a calibrated flow nozzle and a magnehelic pressure gauge. Two propeller anemometers were mounted in between the HiVol samplers to measure the air speed coming out of the enclosure.

The same hopper bottom bin and similar slide gate openings used in air entrainment measurement were used for dust emission measurement. The drop distance from the hopper bin slide gate to the dump pit grate, which was 53 cm, was chosen based on actual drop distance of a 25 tonne-capacity hopper bottom truck. The slide gate settings and the corresponding grain flow rates were: full opening at 118 kg/s (9.2 m^3/min; 15,600 bu/hr), three-fourths opening at 88 kg/s (6.8 m^3/min; 11,600 bu/hr), one-half opening at 55 kg/s (4.2 m^3/min; 7,200 bu/hr) and one-fourth opening at 17 kg/s (1.3 m^3/min; 2,300 bu/hr). There were also three replicates of each grain flow rate.

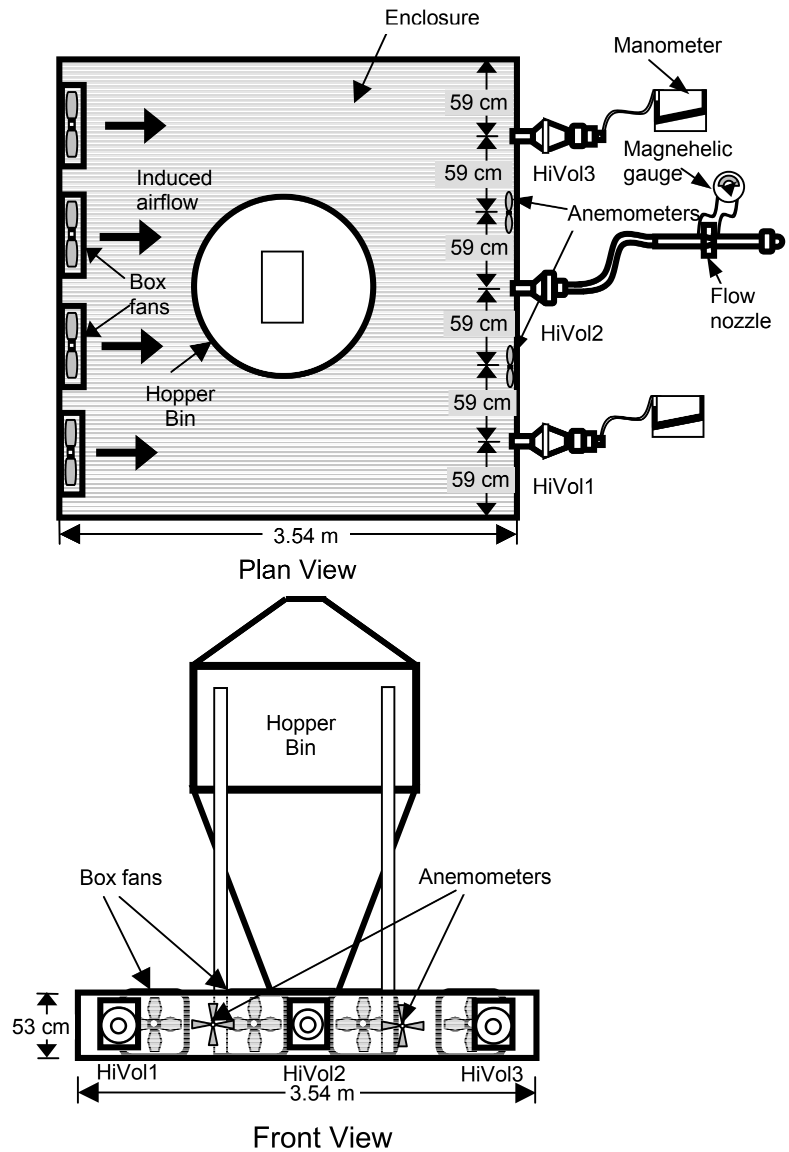


Figure 5. Schematic diagram of dust emission set-up (not drawn to scale).

Test Procedure

Preliminary receiving tests were first conducted to estimate the average air speeds across the enclosure while grain was being dumped. The mean air speed was 50 m/min (approximately 2 mph), ranging from 47 to 54 m/min. This air speed was used to establish the isokinetic sampling flow rates for the HiVol samplers.

The dust collection filters were first weighed in an electronic balance (Mettler Instrument Corp., Highstown, N.J.) with an accuracy of ±0.001 g and were carefully placed in the filter holders. Negligible change in filter weight was observed before and after conditioning at a room kept in a temperature of 22°C and 28 % relative humidity. The sampling flow rates were adjusted with variable voltage transformers to attain isokinetic sampling condition. The box fans and the samplers were turned on approximately 10 sec before unloading the corn to allow the desired sampling flow rate to be reached and were turned off after all the unloaded corn was inside the dump pit. The sampling period covered the entire duration of the receiving test.

The total mass of shelled corn was estimated by taking the product of the corn volume and its bulk density (771 kg/m^3). Voltage signals from the anemometers were recorded at 0.5-sec intervals by the datalogger and converted to air speed using the equation provided by the manufacturer. The volumetric flow rate through the enclosure was estimated by taking the product of the enclosure cross sectional area and the average air speed.

After the box fans and samplers were turned off, the filters were collected and weighed. Dust emission rate, DER, was expressed as the mass of dust per mass of grain:

$$DER = (CQ_e t_d)/(M) \quad (3)$$

where:

C = average concentration of particulate matter collected by the HiVol samplers, g/m^3

t_d = dust sampling time, min (0.9 to 4.4 min)

Q_e = volumetric flow rate through the enclosure, m^3/min (86.2 to 92.5 m^3/min)

M = total mass of corn received, tonnes

Corn sampling and analysis

Samples were collected from the elevator leg as the grain was transferred back to the storage bin through a diverter type mechanical sampler (Carter-Day Co., Minneapolis, Minn.). Moisture content was measured using an automatic grain moisture tester (Motomco Model 919 Seedburo Co.,Chicago, Ill.). Bulk density was determined using a grain scale (Model 8800A, Seedburo Co., Chicago, Ill.). Broken corn kernels and foreign materials (BCFM) content was analyzed with a Carter-Day dockage tester. Three sets of samples of about 3 kg for each grain flow rate setting were collected and analyzed. Results of the analysis of the physical properties of the corn samples are shown in table 1.

Table 1. Mean physical properties of corn samples.

Test conducted	Moisture Content (S.D.) % wet basis	Bulk density, (S.D.), kg/m^3	BCFM (S. D.), %
Air entrainment	11.5 (0.06)	767 (1.2)	18.1 (1.33)
Dust emission	14.1 (0.02)	771 (2.1)	3.3 (0.23)

Analysis of data

The effect of grain flow rate on SE and DER was determined using the General Linear Model (GLM) procedure for analysis of variance (ANOVA) in PC-SAS (SAS Institute, Cary, NC). Differences in SE and DER between grain flow rates were analyzed using Least Square Difference (LSD) method. Linear and non-linear regression analysis was performed for all replicate data (n=12) to describe the relationship between grain flow rate and the parameters measured. A 5% level of significance was used.

Results and Discussion

Air entrainment

Mean values of SE and ranges were 0.27 m^3/m^3 (0.16 to 0.38 m^3/m^3) for full opening (114 kg/s), 0.42 m^3/m^3 (0.36 to 0.50 m^3/m^3) for three-fourths opening (87 kg/s), 0.87 m^3/m^3 (0.73 to 1.08 m^3/m^3) for half opening (47 kg/s), and 2.07 m^3/m^3 (2.04 to 2.13 m^3/m^3) for one-fourth opening

(17 kg/s). Grain flow rate significantly affected SE ($p<0.05$); SE tended to decrease with increasing grain flow rate (figure 6) although the mean SE for grain flow rates of 114 kg/s and 87 kg/s were not significantly different ($p>0.05$). A similar trend was observed in alumina powder (Cooper and Arnold, 1995), which indicates that the air entrainment of each individual particle decreases as the bulk material flow rate increases. The relationship between SE and grain flow rate can be described with the power model:

$$SE = 49.4\,\dot{m}_g^{-1.09}\ ;\ R^2=0.95 \qquad (4)$$

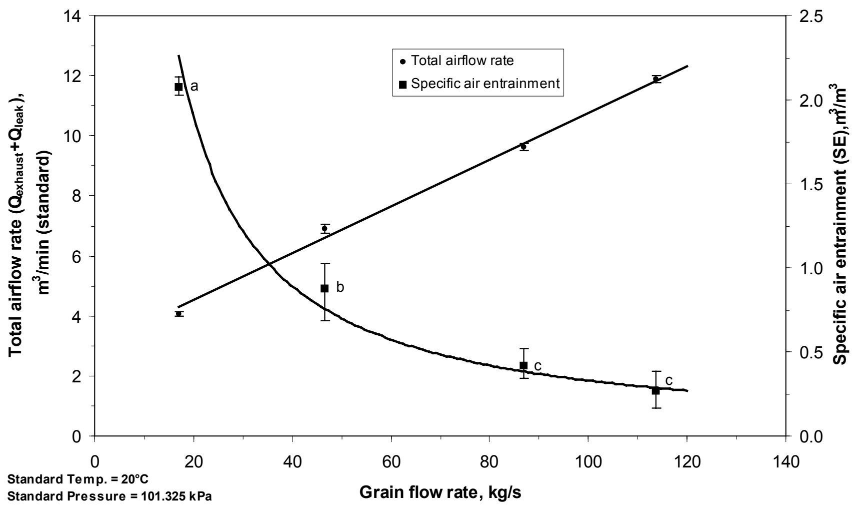


Figure 6. Specific air entrainment, SE, and total airflow rate at different grain flow rate. Bars indicate ± 1 standard deviation. Means of SE having the same letter are not significantly different ($p>0.05$).

The total volumetric airflow rate ($Q_{exhaust}$+ Q_{leak}) increased significantly ($p<0.05$) with increasing grain flow rate (figure 6). This was primarily due to the increase in the amount of displaced air associated with the increased grain flow rate. The linear relationship between total volumetric airflow rate and grain flow rate was described by the model:

$$(Q_{exhaust} + Q_{leak}) = 0.078\,\dot{m}_g + 2.97\ ;\ R^2=0.98 \qquad (5)$$

Dust Emission

The mean DERs and ranges for the different grain flow rates were 8.3 g/tonne (8.1-8.4 g/tonne) for full opening (118 kg/s), 9.0 g/tonne (8.7-9.3 g/tonne) for three-fourth opening (88 kg/s), 12.0 g/tonne (11.1-12.5 g/tonne) for half-opening (55 kg/s), and 14.6 g/tonne (13.7-15.8 g/tonne) for one-fourth opening (17 kg/s). Mean dust concentrations were 0.68, 0.52, 0.43, and 0.16 g/m^3 for grain flow rates of 118 kg/s, 88 kg/s, 55 kg/s, and 17 kg/s, respectively.

Grain dust emissions measured in this study were comparable to those reported in the literature. Shaw et al. (1998) reported dust emissions of 8.5 g/tonne taken at a grain flow rate of approximately 4.5 tonnes/min (75 kg/s), Kenkel and Noyes (1995) reported 9.5 g/tonne of wheat for hopper bottom truck receiving, and the EPA (1998) emission factor for corn receiving with hopper bottom trucks was 17.5 g/tonne.

Mean DERs for the different grain flow rates were significantly different ($p<0.05$). Similar to SE, DER decreased with increasing grain flow rate (Fig. 7). Also, no significant difference ($p>0.05$) was observed between the mean DER of 118 kg/s and 88 kg/s. The dust emission levels during bulk receiving are affected by two main factors: the wind currents in the receiving area and the dust generated by the falling grain stream when it strikes the receiving pit (Wallace, 2000). In this study, the effect of wind current was minimized by using a controlled wind source (i.e., box fans) and closing the doors of the receiving area. Differences in dust emission, therefore were mainly due to the displacement of air from the pit and entrainment of air by the falling grain. The higher emission rates measured at lower grain flow rates were expected due to the higher specific air entrainment. DER can be expressed as a function of grain flow rate using the linear model:

$$\mathrm{DER} = -0.063\,\dot{m}_g + 15.4\ ;\ R^2=0.88 \qquad (6)$$

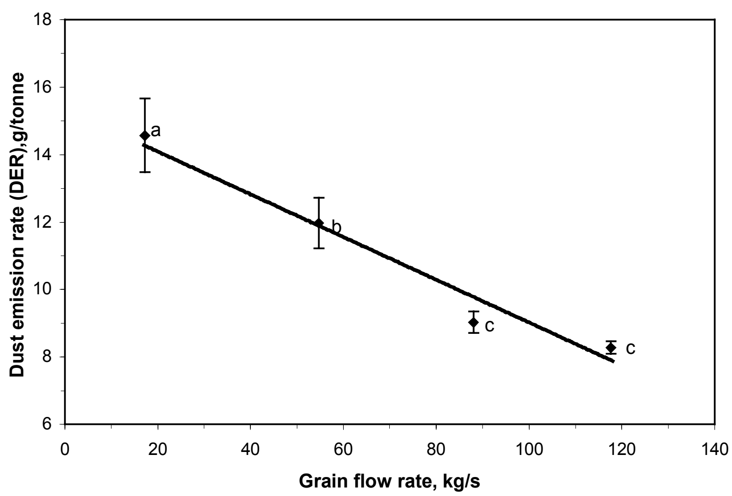


Figure 7. Dust emission rate at different grain flow rate. Bars indicate ± 1 standard deviation. Means having the same letter are not significantly different ($p>0.05$)

Conclusions

This research measured the rates of air entrainment and dust emission during shelled corn receiving as a function of grain flow rate. The following conclusions were drawn:

1. The specific air entrainment decreased in a non-linear relationship with increasing grain flow rate and ranged from 2.07 to 0.27 m^3/m^3 of corn for grain flow rates of 17 to 114 kg/s.
2. Dust emission rates decreased linearly with increasing grain flow rate and ranged from 14.6 to 8.3 g/tonne of grain for grain flow rates of 17 to 118 kg/s. These emission rates were comparable to published data.
3. Total volumetric airflow rate coming out of the pit increased linearly with grain flow rate.

Limitations of the Study and Future Research

Results of this study are preliminary and apply only to the conditions considered. The study has several limitations. First, the research simulated receiving from hopper bottom grain trailers using a hopper bin with a 53-cm drop height. Second, the pit conveyor was not operating during the tests so that no grain was leaving the pit during the tests. If the pit conveyor were operating, some grain would also be flowing out of the pit; this would affect airflow balance, air entrainment, and possibly dust emission. Third, the metal grate was removed and a wooden hopper with sloped guide vanes was used to minimize measurement error for air entrainment. However, this resulted in a longer effective drop height than the normal situation when grain builds up on the grate. Fourth, only total PM was measured; neither PM10 emission nor particle size distribution was determined.

Further research will be conducted to address the above limitations. In particular, air entrainment and dust emission will be measured for actual hopper bottom grain trailers. Experiments will also be conducted with the pit conveyor operating. Possible effect of grain build-up and change in effective drop height will be established. Additionally, the effects of the type of grain, BCFM content, and grain drop height on air entrainment and dust emission rate will be investigated. The degree of percent opening of the dump pit grate assembly, including restrictive dust control baffle assemblies will also be considered. Particle size distribution with emphasis on PM-10 will also be studied.

Acknowledgements

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