Session 4

Engineering for Stored Product Protection and Pest Prevention

Bin coring: a simple practice for improving aeration performance and saving energy

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Abstract

The coring operation consists of removing the center portion of the grain mass, or core of the silosilo, to improve airflow distribution. Additional benefit of this practice is the elimination of a significant portion of the fine material, which is a source of fungal inoculum and feed for insects. The effect of coring on airflow distribution through a grain mass has been previously addressed, but the effect on energy savings was not fully quantified. Thus, the goals of this reseach were: 1) to quantify the airflow increase due to the coring operation of a silosilo full of wheat; and 2) to quantify the reduction on fan runtime and energy consumtion due to improvement in airflow distribution and airflow increase after coring. The effect of coring on airflow was quantified using the AireAr software, and the effect on aeration efficiency was studied through simulation using a specialized software (PHAST-FDM). For levels of coring (0%, 3%, 5% and 8% of total grain mass) and four levels of non-uniformity of airflow (center side difference) (30, 20, 10 and 0) were considered. Results indicated that the coring operation reduced the total time to achieve cooling, number of fan run hours, and fan power consumption. The main effect of the coring operation was the increase in specific airflow (up to 45% increase). Energy savings increased with coring, obtaining savings of 11%, 28% and 30% for 3%, 5% and 8% of coring, respectively. It was concluded that coring the silosilo by unloading from 3 to 8% of the stored grain mass is a recommendable practice, because it increases the specific airflow rate and airflow uniformity, reduces fan run hours and generates energy (and cost) savings.

Keywords: airflow resistance, airflow uniformity, simulation, fine material.

Introduction

One of the most frequent problems in storage facilities is the accumulation of fines in the center (core) of the silosilo. Fine material is defined as pieces of broken grains, foreign matter and weed seeds. Fine material occupies the void spaces in the grain mass, reducing the porosity of grain and increasing airflow resistance (Grama et al., 1984; Haque et al., 1981). When loading a silosilo through the center of the silosilo, fine material tends to concentrate in the center of the grain mass and increasing the airflow resistance in the core. Consequently, air velocity and specific airflow are lower in the core than in the periphery of the grain mass.

The coring operation is one of the most simple and recommended practices for improving the storability of the grain mass. The coring operation consists in removing the center portion of the grain mass, or core of the silosilo. When unloading a silosilo from the center opening in the floor, the first grain to come out is the grain of the core of the silo, which also contains most of the fines concentrated in that location of the grain mass (Bartosik and Maier, 2006). Removing most of the fines from the silo not only improves the airflow distribution, but also reduces the risk of developing insects and molds in that area or the silo.

Bartosik and Maier (2006) measured the concentration of fine material and air velocity at the center and periphery of the grain mass for 15 on-farm natural air/low temperature (NA/LT) in-silo corn drying and conditioning experiments. It was observed that the accumulation of fine material in the core was up to 232% higher than at the periphery. This accumulation of fines at the core of the silo resulted in non-uniform airflow distribution. It was observed that, on average, there was 74% more airflow at the side (close to the silo wall) than at the center of the silo (ranging from 24 to 222%). Simulation was used to study the effect of non-uniform airflow caused by fine material accumulation at the center of the silo and the grain peak produced after loading the silo. They concluded that operators of NA/LT in-silo drying systems could reduce drying costs from 25 to 33% by leveling the grain peak after loading the silo. Additional reductions in drying costs from 18 to 22% could be achieved by installing effective grain spreaders or by coring the grain mass. Later, Lawrence and Maier (2011) developed a non-uniform airflow model using the finite volume method to predict air velocity for cored, peaked and leveled grain mass configurations.

Coring silos for long term storage, even though a known practice among elevator managers, it is not consistently implemented. Typically, during coring from 3 to 8% of the grain mass is unloaded. Cardoso et al. (2008) evaluated the fine material distribution in wheat silos and the effect on airflow. They found that unloading about 3% of the grain mass was required to remove most of the fines. Additionally, they concluded that the coring operation can increase not only the airflow uniformity but also the total airflow in the silo.

Simulation was used in the past to quantify the effect of fine material and non-uniform airflow on the performance of natural air/low temperature in-silo drying systems (Bartosik and Maier, 2006) with the PHAST-FDM model. However, not sufficient information was generated about the improvement in airflow distribution due to the coring operation, amount of grain to be unloaded during coring, reduction of the cooling time during aeration, and potential energy consumption reduction derived from this best management practice.

Thus, the goals of this reseach were: 1) to quantify the airflow increase due to the coring operation of a silo full of wheat; and 2) to quantify the reduction on fan runtime and energy consumtion due to improvement in the airflow distribution and airflow increase after coring.

Materials and Methods

Airflow estimation

The metal silo considered for this study had a cone botton with 30° inclination, 8.5 m diameter and 10 m heigh to the eave, with a centrifugal aeration fan of 2 HP (1.49 KW) (Chicago Blower, SQDA Agro-200 – 1410 RPM). The grain considered for the study was wheat at 14% moisture content (m.c.) and test weight of 76 kg/hl (0.76 t/m^3).

The effect of the coring operation on total airflow was evaluated with the AireAr software (http://online.inta.gov.ar:8080/aireAr/mainMenu). This software compares the performance curve provided by the fan manufacturer with the system airflow resistance curve computed with the Shedd equation and the set of parameters provided in the ASABE standard for wheat (ASAE, 1999) (a= 8,410, b= 2.72, Multiplier = 1.2) (Fig. 1), and estimates the resistance and the total and specific airflows in the silo (Bartosik et al., 2009).

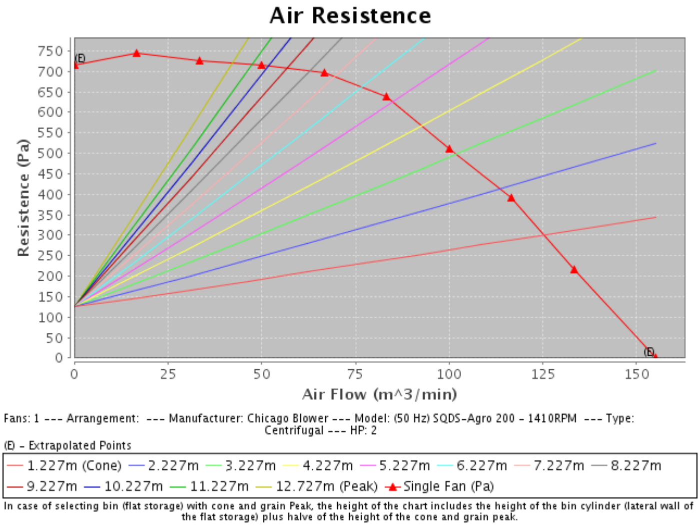

Fig. 1. Screen capture of the AireAr software showing the fan performance curve and the airflow resistance curves for the base condition.

The base silo configuration, before coring, had a grain peak of 3.0 m at the center with a total capacity of 509.6 t, and a multiplier of 1.2 was considered in the Shedd equation to account for the packing effect of the grain on airflow resistance. Three coring alternatives were evaluated (3%, 5%, 8%), which resulted with different differential height in the grain peak and different amounts of stored wheat. Additionally, the Shedd equation multiplier was proportionally reduced according to the coring percentage to account for the “loosening” effect in the grain mass, which reduces airflow resistance (Table 1).

Table 1. Height differential of the grain peak at the center of the silo, amount of unloaded grain and amount of remaning grain in the silo before and after coring.

Parameter	Base condition (Before coring)	After coring		
		3%	5%	8%
Shedd multiplier	1.2	1.1	1.05	1.0
Peak heigh differential (m)	3	1.95	1.2	0
Amount of grain (t)	509.6	494	484	468
Amount of unloaded grain (t)	-	15.6	25.6	41.6

Aeration simulation

The Purdue Post-Harvest Aeration and Storage Simulation Tool – Finite Difference Method (PHAST-FDM) is a numerical model that solves the heat and mass transfer during in-silo drying and conditioning in two dimensions (x, y) (Bartosik, 2005). To solve the problem of non-uniform airflow rate through the grain mass, PHAST- FDM simulates two grain columns: one for the core, and the other for the periphery. The heat and mass transfer equations are solved independently for each column, and the model assumes no interaction between them. PHAST-FDM accepts different non-uniformity factors (NUF) for airflow rates that can be entered by the user. The NUF was defined as the center-periphery difference with respect to the average airflow rate: (airflow periphery – airflow center / [(airflow periphery + airflow center) / 2] × 100). For instance, an NUF of 30% for an average airflow rate of 1 m/s indicates that the airflow rate is 0.85 m^3/(min t) at the center of the silo and 1.15 m^3/(min t) at the periphery. The PHAST-FDM model with the center-periphery differential airflow rates was validated for predicting MC changes in different grain layers for several on-farm NA/LT in-silo drying tests (Bartosik, 2005; Bartosik and Maier, 2006).

The initial average conditions for the cooling aeration simulation were 14% m.c. and 30°C temperature. It was assumed that the wheat was harvested on January first at Balcarce, South-East Buenos Aires province, Argentina. The final condition for the simulation was achieved when wheat reached 18°C average temperature and 19°C maximum temperature. The PHAST-FDM model was supplied with hourly temperature and relative humidity data of 13 different years. The silo considered had the same configuration as decribed in the previous section. The simulated aeration strategy turned on the fan whenever the ambient temperature was below 18°C. The airflow was obtained with the AireAr software as described in the previos section for four different coring percentages (0 (before coring); 3; 5 and 8%). Four NUF levels were considered (30 (before coring); 20; 10 and 0). A NUF of 30 represents the situation before coring, in which the difference in airflow between the center and periphery of the gran mass was the greatest, while a NUF of zero means that the airflow distribution was completely uniform (perfect coring).

Table 2. Combinations of specific airflow rates obtained for different coring percentages and non-uniformity factors considered for the aeration simulations with the PHAST-FDM model.

Non-Uniformity Factor	Coring percentage			
	0	3	5	8
30	X *	-	-	-
20	-	X	X	X
10	-	X	X	X
0	-	X	X	X

* Base line corresponding to the silo condition before coring

Energy savings

Energy savings due to the coring operation was computed taking into account the fan electrical power consumption (kWH) and substracting the electrical power needed to unload the silo for the coring operation. Fan power consumption was obtained by multiplying the fan runtime hours obtained for each simulation condition by the fan power (kW). For computing the electrical power consumption related to coring (unloading the silo) it was assumed a silo unloading auger of 5.5 kW and a bucket elevator of 11 kW were used with a conveying capacity of 60 t/h. The coring operation time was estimated as 0.0, 0.26, 0.49 and 0.63 hours for coring conditions of 0, 3, 5 and 8%, respectively, and the corresponding power consumption values were 0, 4.29, 7.04 and 11.44 kWH.

Results

Airflow estimation

Before coring, the silo full of wheat had a total capacity of 509.6 t, with a grain peak of 3 m at the center. Under that condition, airflow resistance against the fan was 720 Pa, which resulted in a total airflow rate of 42.1 m^3/min. Thus, before coring, the specific airflow was 0.083 m^3/(min t). The coring operation increased the specific airflow in three ways. First, after coring there is a lower grain depth, which reduces the airflow resistance and, hence, the total airflow provided by the fan increases. Second, the “loosen” effect of the coring further reduces the airflow resistance, which also increases the total airflow. Third, as the total amount of grain in the silo decreased, the specific airflow increased. Table 3 shows the total airflow, speficic airflow and airflow resistance for the different configurations considered in the study.

Aeration performance

The speficic airflows obtained in Table 3 were used as input in the aeration simulation runs carried out with the PHAST-FDM program for the four coring levels. Table 4 shows the average results of 13 years of simulation for each evaluated condition (coring % from 0 to 8%, and NUF from 30 to 0). In the base situation (before coring and NUF of 30), the total time to complete cooling from 30°C to less than 18°C was 1055 h (44 days). The accumulated fan runtime was 307 hours (fan was “on” 29%

of the time), and the aeration power consumption was 457.4 kWH. The final grain condition was 13.7% m.c. and 17.6°C.

Table 3. Total airflow provided by the fan, specific airflow and static pressure in the aeration system before coring and after different coring percentages.

Parameter	Base condition (Before coring)	After coring		
		3%	5%	8%
Total airflow (m^3/min)	42.1	47.6	51.4	55.9
Specific airflow (m^3/(min t))	0.083	0.095	0.108	0.12
Airflow resistance (Pa)	720	716	713	708

As the percentage of coring increased, the total time to complete cooling and the fan runtime hours decreased, while the energy savings regarding the base situation (no coring) increased.

Coring 3% of the grain mass resulted in a reduction of the total time to complete cooling to 909 hours and fan runtime hours to 269 hours. The aeration power consumption was 400.8 kWH, while the electrical power consumed by the unloading auger and the bucket elevator for the coring operation was 4.29 kWH. This resulted in an average energy saving of 52.3 kWH or 11% of the base condition.

For a coring percentage of 5%, the total time to complete cooling was reduced to 761 hours and fan runtime hours to 216 hours. The resulting aeration power consumption was 321.3 kWH, while the electrical power consumed by the unloading auger and the bucket elevator for the coring operation was 7.04 kWH. This resulted in an average energy saving of 129.0 kWH or 28% of the base condition.

For a coring percentage of 8%, the total time to complete cooling was further reduced to 727 hours and fan runtime hours to 207 hours. The resulting aeration power consumption was 308 kWH, while the electrical power consumed by the unloading auger and the bucket elevator for the coring operation was 11.44 kWH. This resulted in an average energy saving of 138.1 kWH or 30% of the base condition.

As the resulting airflow after coring became more uniform (NUF decreased from 30 to 0), the total time to complete cooling and the fan runtime hours decreased, while the energy saving regarding the base situation (no coring) increased. Across all percentages of coring, fan runtime hours and energy savings regarding the base condition (no coring and NUF of 30) for a NUF of 20 were 234 hours and 22.1%, respectively, while for a NUF of 0 (no airflow difference between center and side) the fan runtime decreased to 228 hours and the energy saving increased to 24.2%.

Table 4. Results of the PHAST-FDM simulation runs showing the time to complete cooling, fan runtime, aeration power consumption, and average final moisture content and temperature, and the computed coring electrical consumption and total energy saving due to coring for the four coring levels evaluated.

Coring	**NUF**	**Time to complete cooling (hs)**	**Fan runtime (hs)**	**Aeration power consumption (KWH)**	**Coring power consumption (kWH)**	**Energy saving (kWH)**	**Final average m.c. (%)**	**Final average temp. (°C)**
Before (0%)	**30**	1055	307	457.4	0	0	13.7	17.6
3%	**20**	916	272	405.2	4.29	47.8	13.7	17.5
	10	909	269	400.8	4.29	52.3	13.7	17.5
	0	902	266	396.3	4.29	56.8	13.7	17.6
	Avg	909	269	400.8	4.29	52.3	13.7	17.5
5%	**20**	770	217	323.3	7.04	127.0	13.7	17.6
	10	757	215	320.3	7.04	130.0	13.7	17.6
	0	757	215	320.3	7.04	130.0	13.7	17.6
	Avg	761	216	321.3	7.04	129.0	13.7	17.6
8%	**20**	752	213	317.4	11.44	128.6	13.7	17.5
	10	717	205	305.4	11.44	140.5	13.7	17.5
	0	713	202	301.0	11.44	145.0	13.7	17.6
	Avg	727	207	308	11.44	138.1	13.7	17.6

Discussion

The coring operation has a main effect of increasing the specific airflow for aeration. As a portion of the grain is unloaded, the total depth of grain is reduced, the path of the air through the grain mass is shortened, and the airflow resistance is reduced. An additional reduction in airflow resistance is obtained by the "loosening" effect of the grain mass. As a result of the reduction of airflow resistance, the fan total airflow increased (Table 3). The airflow increase depends on the characteristics of the fan (fan performance curve shape) and the operational condition of the fan. For instance, if the aeration fan has a performance curve that does not change much with static pressure (e.g., a high speed centrifugal fan), then the reduction in airflow resistance due to coring will have little effect on total airflow, and vice versa for an axial fan (with a fan performance curve that changes with static pressure). In addition to the increase in the total airflow, the specific airflow also increased due to the reduction in the amount of grain after coring. In this study, the increase on specific airflow was estimated up to 45%. Cardoso et al. (2008) reported an increase of 63% in the measured airflow after 3% of coring a silo with 700 tonnes of wheat.

The simulation of the effect of coring on airflow performance showed that the coring operation reduced the total time to achieve cooling, the fan runtime hours, and the fan power consumption. The reduction in fan power consumption was achieved through the reduction in the fan runtime hours. The electrical power consumption of the unloading auger and bucket elevator for coring the silo was always lower than the savings achieved, implying that coring always has an economical benefit (Table 4). The energy saving increased with coring, obtaining an energy saving of 11%, 28% and 30% for 3%, 5% and 8% of coring, respectively. Based on these results, 5% of coring was the most convenient, because this amount of coring had the larger marginal benefit in energy savings.

The improvement of airflow uniformity after coring also reduced the fan energy consumption, although to a lesser extent. For a NUF of 20 the total energy savings was 22.1% (across all coring percentage levels) while for a NUF of 0 (no airflow difference between center and side) the energy savings only increased to 24.2%. This implies that the main benefit of coring was through the increase in the specific airflow.

Additional benefits of coring, besides energy savings, also must be considered. A reduction in the time for achieving cooling objectives has consequences reflected in the final quality of the grain. For instance, total cooling time for the base condition was 1055 hours, while 5% of coring with a NUF of 0 shortened the total cooling time to 757 hours. Shortening cooling time by 12 days may provide important benefits preventing insect development (Navarro and Donahaye, 2005). Additionally, coring removes a significant proportion of the fine material from the silo (Cardoso et al., 2008), and fine material was reported to have higher mycotoxin concentration than whole grain (Abbas et al., 1985).

Thus, coring the silo by unloading from 3 to 8% of the stored grain is a recommendable practice, because it increases the specific airflow and airflow uniformity, reduces fan runtime hours and generates energy (and cost) savings. Additionally, by reducing the cooling time and eliminating the fine material reduces the risk of insect development and mycotoxins formation.

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Application of transverse ventilation in grain storage in China

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Extended abstract

In China, mechanical ventilation technology has been researched and applied since the 1950s. Beginning in 1998, large-scale grain warehouses started to be built with national government support. The mechanical ventilation technology, namely the "four-in-one" technology, was promoted enormously during this period. In the “four-in-one” system, the aeration technology was based on the vertical aeration system with ventilation ducts temporarily fixed on the floor of the warehouse. The airflow passed vertically through the grain bulk from the bottom to the surface or vice versa with air being pushed by fans, and the heat and moisture from the grain exchanged with the air during vertical aeration. This vertical ventilation system has been widely used for the last twenty years, but it is complex and inconvenient, and also air distribution is uneven.

To fix these problems, Chinese researchers developed a new transverse ventilation technology as shown in Fig. 1. In this system, aeration ducts are mounted along the opposite interior walls of the warehouse and air travels horizontally through the grain mass. A large number of pilot scale tests and warehouse applications have been done from 2010 to 2014.

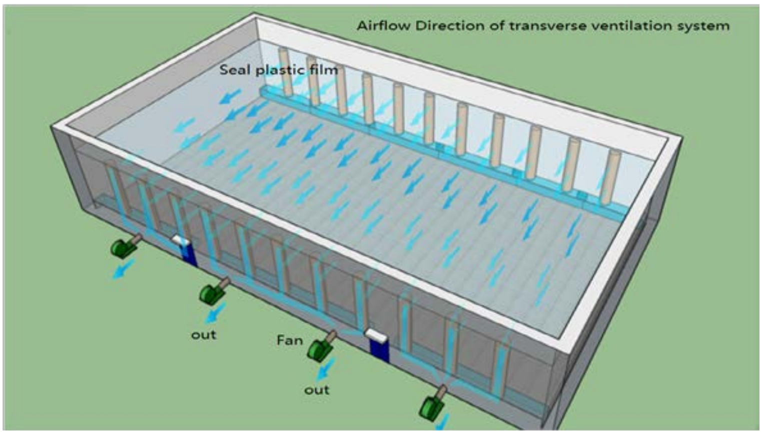

Fig. 1 The new transverse ventilation system.

The grain surface is sealed by plastic film during storage to prevent air from escaping through the surface layer during aeration and gas during fumigation. During aeration, the airflow is sucked from