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Chilled Aeration to Control Pests and Maintain Grain Quality During the Summer Storage of Wheat in North Central Region of Kansas

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Abstract

Chilled aeration allows to cool grain, independent of ambient conditions, to "safe" temperatures where insect, fungi, and spoilage is reduced to the minimum. The objective of this research was to evaluate the advantages of using grain chilling to preserve the quality of grain and reduce post-harvest losses, compared to conventional aeration and storage strategies used during the summer storage of wheat in Central Kansas, U.S.A. The research trials were developed in two 1,350 metric ton (t) steel silos in a Farmer's Cooperative during the summer and fall of 2015 and 2016. One of the silos was chilled and the other was used as a control managed by the Cooperative. Variables evaluated were: grain temperature, moisture content (MC), grain quality, insect development and reproduction rate. The chilling treatment reduced the grain temperature from 28°C- 39°C to a minimum of 17°C-17.6°C in less than 250 hours. Grain temperatures below 25°C were not possible during the summer using ambient aeration. Minimum variation of MC was observed in the Chilled silo while ambient aeration reduced the MC by 0.5%. Reproduction rates of RFB and LGB were significantly reduced by chilled temperatures lower than 17°C. Lower temperatures also reduced insects discovered in probe traps and insect damaged kernels (IDK). The energy cost of the grain chiller was between 0.26 US $/t- 0.32 US $/t higher than ambient aeration.

Keywords: Ambient aeration, Grain chilling, Summer storage, Post-harvest losses, Wheat.

Introduction

Grain that is harvested during the summer season of the Northern Hemisphere presents the inconvenience that it is collected when the ambient temperature is high (26°C to 40°C). In these conditions, the grain goes into storage at a high temperature, which makes it prone to immediate insect infestation and mold growth that can affect its quality. Therefore it is imperative that the grain temperature is decreased as soon as possible (Reed and Arthur, 2000). Nevertheless, cool ambient conditions may be limited during this part of the season, thus the use of chilled air could be considered as a solution. Chilled air refers to aeration air that is cooled before it comes contact with the grain by passing through an evaporator coil of a grain chilling unit (Maier and Navarro, 2002). When the chilled air comes in contact with the grain, it lowers the temperature of the grain, independent of ambient conditions (Maier and Navarro, 2002). This technology makes it possible to cool down grain temperature between 20°C and 15°C immediately after summer harvest, which reduces insect populations and consequently the need for chemical control (Navarro et al., 2002).

Based on field tests using chilled aeration on low-moisture wheat stored in Michigan, Maier (1992) simulated chilling in the Midwestern region of the U. S. The computer simulation showed that chilled aeration was capable of lowering the temperature of 579 metric tons (t) of wheat from 30°C to 15°C in just one week. Continuous ambient aeration took 1.5 times longer to cool the grain down to 10°C, which caused higher dry matter losses (DML). Other grain chilling field trials developed in 2,500 t wheat silos in Central Kansas determined that the cost of chilling the grain from 32°C- 35°C to 15°C– 17°C in six days was less than 0.16 US $/t, while the cost of fumigating and turning the non-aerated silo was 0.67 US $/t, plus the additional shrink loss cost of approximately 7.5 t from the bulk (Hellemar, 1993).

Maier et al. (1996) compared eight combinations of ambient aeration, fumigation and chilled aeration strategies in three different locations of the U.S. through computer simulations. Chilling the grain below 17°C in a short period of time proved to be the best strategy to avoid DML and reduce the populations of maize weevil (MW) *Sitophilus zeamais*.

While the strategy of chilling grain is the effective control of insects, there are other benefits that come from the grain chilling technology, such as the possibility of storing damp grain for a limited time, predictable drying capability and better preservation of end-use quality (Hellemar, 1993; Maier and Navarro, 2002).

The objective of this research was to evaluate the advantages of using grain chilling technology to preserve the quality of grain and reduce post-harvest losses caused by insects and fungi, compared to the conventional aeration and storage strategies used during the summer storage in North Central Kansas.

Materials and Methods

This research was conducted at Farmer's Cooperative in the North Central region of Kansas, U.S.A., from August to November 2015 and from June to September 2016. The research trials were conducted in two 1,350 t steel silos of 11.3 m in diameter and 16.8 m in height from the bottom to the eave, filled almost completely with hard red winter wheat (HRW) harvested in the summer of

2015 and 2016. Before each harvest, the silo walls were cleaned up to 6 m from the bottom and the remaining grain on the floor of the silo was vacuumed out. Attached to these silos there were two centrifugal fans in parallel, each with a 10 HP (7.5 kWh) motor (Baldor Electric Co., Fort Smith, AR). One of the silos was chilled (Chilled silo) and the other one was used as a treatment control (Control silo) managed by the Cooperative using their regular grain quality management strategies.

Grain chiller setup and monitoring of air and grain conditions

The grain chiller GCH-20 used in this project was facilitated by the Brazilian company Coolseed (Santa Tereza do Oeste, Brazil). This equipment has the rated capacity to chill 100 to 170 t per 24-hour continuous operation in silos of up to 1,800 t, according to specifications of the manufacturer.

The grain chiller was connected to the grain silo through thermally insulated ducts that were connected into the two inlets of the aeration fans that where removed from the (Figure 1).

Figure 7. Grain chiller GCH-20 setup: (a) Insulated duct connected to the chiller's outlet at one end and to a "T" connector at the other, (b) Two ducts attached to the fan transition parts of the aeration fans that were removed.

The conditions inside the Chilled and Control silo were monitored through three temperature cables (TSGC Inc., Spirit Lake, IA) in each silo, that were attached to the roof and the floor of the silo. Additionally, temperature and relative humidity (RH) sensors were placed in the fan transitions, outside of the silos to record ambient conditions. In the 2016 trials, additional sensors were placed in the fan outlet of the grain chiller and inside the insulated ducts.

The wheat moisture content (MC) was measured using a GAC 2500-UGMA (Dickey John, Auburn, IL) every 30 days. Grain samples were taken at four different depths and three depths in each of the silos. The samples collected per location were put together and homogenized to make up a composite sample per location in each of the silos. The composite sample from each location was considered a replication for the calculation of significant differences between sampling dates. Statistical analysis was performed using the SAS statistical software (SAS Institute Inc., NC). Statistically significant differences were analyzed with Tuckey's test ($p < 0.05$).

Insect pest population monitoring and quantification

Insect bioassays

The effect of chilled aeration on the survival rates of insects was quantified using insect bioassays with the species Lesser Grain Borer (LGB) *Rhyzopertha dominica* and Red Flour Beetle (RFB) *Tribolium castaneum*. The bioassays consisted of plastic jars of 0.2 L with holes on the bottom and top, covered with wire mesh and filled with an exact number of adults of each species, together with a mix of flour, yeast and broken kernels for insect feeding.

In each of the silos, a bioassay of each species was located in the center of the silo and next to each temperature cable, and buried 0.3 m below grain surface. A fifth bioassay per species was located in one of the fan transition parts. In 2016, three jars per location were put inside the grain mass and transition parts. One jar from each location was taken out every 28 days.

When the jars were taken out of the silos in each sampling date, the number of dead and live adults were quantified and then discarded, and the larvae, pupae and eggs (if any) were kept in a growth chamber and counted 28 days after as adults. The total progeny number was calculated by the total insect count (initial dead and live insects when jar was pulled out of the silo plus the progeny number after 28 days in the growth chamber) minus the original number of insects put into the jar. Statistical analysis was performed using the SAS statistical software. Statistically significant differences were analyzed with Tuckey's test ($p < 0.05$).

Endemic insect population sampling

Insect populations inside the silos were quantified by placing five perforated insect probe traps model Storgard W.B. Probe II (Trece Inc., Adair, OK) of approximately 0.6 m in length in the North, South, East, West, and Center sections of the silos, approximately 1.5 m from the walls. Insects inside the probe traps were checked every 28 days and identified (up to the genus level). Adults of the main insect pests of stored-products were counted.

Grain quality analysis

Grain samples for these analysis were collected using the same procedure described to collect the MC grain samples. In 2015, the samples were only collected in the first two months of the trial, while in 2016, the sampling period was expanded for one more month.

For the grain quality analysis, only one composite 2,500 g composite sample was taken per silo each sampling date. This composite sample was sent to the Kansas Grain Inspection Service (KGIS) in Topeka, Kansas, for grading.

Electrical cost of chilled and ambient aeration strategies

The energy consumption during the chilling treatment was measured using a kWh counter that was installed at the of the power inlet of the grain chiller. The energy consumed by the aeration fans in the Control silo were calculated according to the hours of operation reported by the Cooperative. The costs of the ambient and chilled aeration process were calculated based on the energy consumption, using an average cost of 0.084 $/kWh (obtained from the local electrical service provider), and considering additional charges for basic service and consumption fees.

Results and Discussion

Ambient and chilling aeration trials

Trial of 2015

The grain chilling treatment started on August 22nd, and the cool air front reached the top of the grain mass after 175 hours of active chilling at an airflow rate of 0.07 m^3/min/t and at a temperature of approximately 17°C (initial grain temperature: 28°C). Due to technical difficulties with the grain chiller during certain periods, the equipment was left running longer to tests its capacity, until September 14th, 2015, for a total of 314 hours (Figure 2).

The ambient aeration strategy applied in the the Control silo by the Farmer's Cooperative was based on turning on the fans when the ambient temperature was below 27°C in the summer, and below 18°C during the fall. The total active aeration time was 308 hours, at an average airflow of 0.11 m^3/min/t. Temperatures inside the Control silo remained over 17°C until mid-November, which was about two months after this temperature was reached in the Chilled silo. According to Hagstrum and Subramanyam (2006), for every month that cooling is delayed, populations of insects can grow 5- to 25-fold their original frequency.

During the trial, the ambient air fluctuated between 8°C and 37°C, with an average of 23°C. The average ambient RH was 63.5% with a minimum of 27.4% and a maximum of 93.1%.

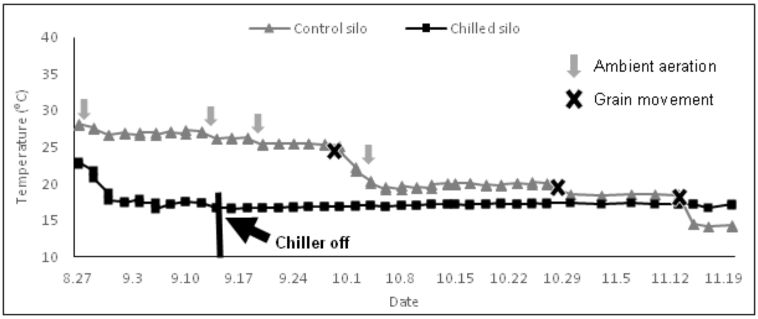

Figure 8. Grain temperature profile (°C) of the grain mass inside the Control and Chilled silo from Aug. 27th to Nov. 20th, 2015 in Farmer's Cooperative, Kansas, U.S.A.

In 2015, the average MC inside the Chilled silo was 11.4% and did not change significantly, while in the Control silo the average MC decreased significantly from 11.1% to 10.5% in the last two months (October and November) of evaluation.

Trial of 2016

In 2016, the initial grain temperature in the Chilled silo was higher than the previous year (39°C). The grain chilling trial started on June 21st, and reached the top of the grain mass after 245 hours of active chilling at aproximately the same airflow rate and temperature as the previous year. Once again, there were some issues with the grain chiller so the equipment was left running longer until July 12th, 2016, for a total of 384 hours (Figure 3).

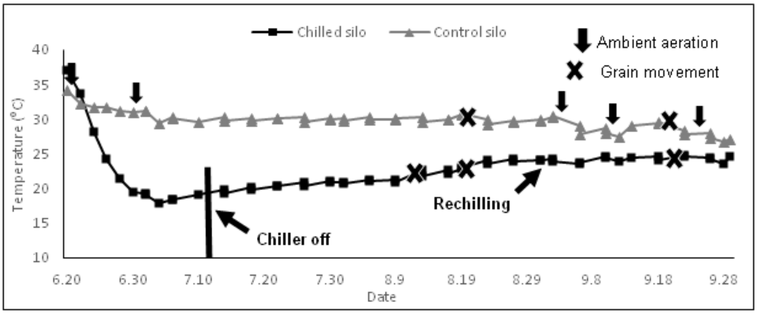

Figure 9. Grain temperature profile (°C) of the grain mass inside the Control and Chilled silo from June 20th to Sep. 29th, 2016 in Farmer's Cooperative, Kansas, U.S.A.

The additional temperature/RH sensors placed in the chiller outlet and insulated ducts in 2016 showed that the temperature of the chilled air coming out of the grain chiller was 12.5°C and increased by an average of 3°C in the transition parts. As well, the RH coming out of the grain chiller was 85% and decreased by an average of 13% in the transition parts.

During the chilling period, the average ambient temperature was 26°C, with 16.5°C and 38°C as minimum and maximum, respectively. The average relative humidity was 63.8%, with 22.7% and 91.2% as minimum and maximum, respectively.

Due to the high ambient temperature during most of July (over 32°C), the issues with the grain chiller, and the constant movement of grain, it was difficult to maintain the temperature of the grain below the optimum insect development threshold (25°C to 33°C) (Fields, 1992), so a rechilling treatment was proposed by early-September, but the issues of the grain chiller persisted and the rechilling cycle did not have much of an effect on the grain temperature.

In the Control silo the initial grain temperature was 34°C. The aeration fans were activated using the same criteria as the previous year. The total fan run hours were 371 and the lowest temperature achieved was 25°C by late September.

In 2016, the average MC inside the Chilled silo was 10.2% and did not change significantly, while in the Control silo the average MC decreased significantly from 10.6% to 10.0% in the last sampling date (September). This was about the same tendency observed in 2015.

During the night of September 29th, one of the eaves from the Chilled silo cracked and a side of the silo split open. Given the incident it was decided to terminate the trial on this date.

Effect of grain chilling on insect reproduction and survival

During the 28 days the bioassays were inside the silos in 2015, the average temperature in the grain surface and fan transition part of the Chilled silo was 19°C and 17°C, respectively, while in the Control silo it was 27°C and 25°C, respectively. The cooler temperatures inside the Chilled silos significantly slowed down the total progeny development of LGB and RFB compared to the progeny observed in the Control silo (Table 1).

The temperatures of 17°C and 19°C in the top of the grain mass and transition part of the Chilled silo, respectively, are considered "safe" since population growth is almost insignificant at these temperatures (Navarro et al., 2002).

Table 2. Total progeny number (mean±SE) of adults of LGB and RFB for 2015 bioassays located 0.3 m below grain surface and in fan transition parts of the Chilled and Control silo for 28 days.

Year	Insect species	Location in the silo	Silo Chilled	Silo Control
2015	LGB	0.3 m below grain surface	2.3 ±0.7^{B}	974.3 ±33.7^{A}
		Transition	1.0	768.0
	RFB	0.3 m below grain surface	5.3 ±1.4^{B}	21.3 ±5.6^{A}
		Transition	0.0	7.0

[A, B] Mean values with the same letter within the same line are not significantly different by Tuckey's test ($p>0.05$).

The difficulty to maintain temperatures below 20°C in the Chilled silo during 2016 due to issues with the grain chilling unit, higher ambient temperatures and constant loading of warm wheat from the field during the trial, did not allow a significant difference to be observed between the insect progeny of the Chilled and Control silo. The average temperatures inside the Chilled and Control silo during the 68 days the bioassays were inside the silos were 23°C and 31°C, respectively. Although the average temperature inside the Chilled silo was lower, the fast temperature rise due to several issues previously mentioned caused an acclimation effect that basically eliminated the cooling effect on the development rate. According to Burks et al. (2000), if the temperature increases after the insect has been exposed to non-lethal cold temperatures, it may recover from the mild cold-injury effect.

Insect populations in the Chilled and Control silos

The main insect pests found in the probe traps of both silos were: flat grain beetle (FGB) *Cryptolestes* spp., flour beetle (FB) *Tribolium* spp. The populations of these genera increased faster in the Control silo than in the Chilled silo in both years (Table 2), even though the temperature difference between the silos was narrower in 2016.

Table 3. Total number of insects of main stored-product pests found in probe traps of Chilled and Control silo on Aug. 15th, Sep. 22nd and Nov. 20th, 2015, and Aug. 2nd, Sep. 20th and Sep. 30th, 2016.

Silo	Insect species	2015 08/15	2015 09/22	2015 11/20	2016 08/02	2016 09/20	2016 9/30^{x}

	FGB	27	84	131	9	171	¥
Chilled	FB	1	80	74	5	78	¥
	WEV	0	10	270	1	29	¥
	FGB	33	3280	1236	44	719	328
Control	FB	4	1350	142	13	722	1241
	WEV	1	0	1	0	8	12

[¥]Probe traps lost when the Chilled silo cracked.

[x]Trial terminated earlier due to the accident in Chilled silo.

The main internal insect pest found in the probe traps were weevils (WEV) of the genus *Sitophilus* spp. More individuals of this genus were found in the Chilled silo than in the Control silo and the reason could have been that this genus was in competitive disadvantage with the high populations of FB and FGB.

Grain quality evaluation

The grain quality results indicate that there was no change in grade throughout the trials in either of the silos (Table 3). This means that there was no noticeable quality deterioration of the wheat during the duration of the trials.

In 2015, one IDK was identified in the Chilled silo in each sampling date which indicates that, although this damage was present before the grain chiller was turned on, it did not increase, probably due to the chilled temperatures (Table 2).

Table 4. Grain quality analysis of wheat stored in Chilled and Control silos from samples taken on Aug. 15th to Sep. 22nd, 2015, and July 1st to Sep. 27th, 2016.

Year	Sampling date	Chilled silo			Control silo		
		July	**August**	**September**	**July**	**August**	**September**
2015	**Insect Damaged Kernels (#/100 g)**	-	1.0	1.0	-	0.0	0.0
	Grade	-	1	1	-	1	1
2016	**Insect Damaged Kernels (#/100 g)**	0.0	0.0	0.0	0.0	0.0	1.0
	Grade	1	1	1	1	1	1

In 2016, IDK increased in the Control silo after three months of storage, while there was no detection in the Chilled silo. This means that, although internal-feeding insects were detected in both silos according to the results of the probe traps, it seems like the slightly lower grain temperature in the Chilled silo discouraged the insect damage.

Power consumption and cost analysis

The total power consumption and cost per ton of the ambient aeration and grain chilling trials are shown in Table 4.

In both years, the cost of grain chilling nearly doubled that of ambient aeration. These results agree with those reported by Quirino et al. (2013). Nevertheless, it has to be taken into consideration that the temperature of the Chilled silo was taken down to levels considerably lower (approximately 17°C) in only 175 hours in 2015 and 245 in 2016, with basically no considerable shrinkage loss. It also has to considered that the cost analysis did not include fumigation cost as these were not required during the trials, but previous research trials have demonstrated that grain chilling is economicallly feasible compared to the use of ambient aeration plus fumigation. Maier et al. (1997) determined that the annual operating cost for chilling wheat from 25°C- 27°C to 15°C- 17°C in 182-240 hours would lower the costs by 1.48 $/t compared to in-house fumigation combined with ambient aeration.

Table 5. Power consumption (kWh) and metric ton ($/t) for running chilling and ambient aeration in 2015 and 2016.

Year	Silo	Average Load (kWh)	Hours of Operation	Total Energy Consumption (kW)	$/t[3]
2015	Chilled	28[1]	314	8,794	0.54
	Control	15[2]	308	4,620	0.28
2016	Chilled	28[1]	384	10,752	0.66
	Control	15[2]	371	5,565	0.34

[1] Average load of system: 1 centrifugal fan of 7.5 kW+ 2 axial fans of 950 W/ea+ 2 compressors of 9.325 kW/ea.
[2] Two centrifugal fans of 7.5 kWh/ea. connected to the Control silo.
[3] Based on an average cost of 0.084 $/kWh

Conclusions

The grain chiller GCH-20 was capable of lowering the temperature of 1,350 t of wheat from 28°C-39°C to approximately 17°C in less than 250 hours. The shrinkage loss with the grain chilling treatment did not significantly increase in either of the trials. Using ambient aeration, the average grain temperature inside the Control silo remained over 25°C all summer during both years and there was a significant shrink loss of approximately 0.5%.

The stable low grain temperatures of 17°C in the Chilled silo in 2015 significantly slowed down the development rate of RFB and LGB, but in 2016, the increasing trend of the grain temperature in the Chilled silo from 17.6°C to more than 25°C avoided this effect to be observed.

The lower grain temperatures in the Chilled silo decreased drastically the progeny development of FGB and FB in both years. The most common internal-feeder found in the probe traps was the WEV, although proof of increasing levels of IDK were only found in the Control silo in 2016.

The cost analysis of the trials, based only on the power consumption of both aeration strategies, showed that the cost of grain chilling is between 0.26 $/t- 0.32 $/t higher than ambient aeration.

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Does it really work? 25 years biological control in Germany

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Stored-product protection, museum environments as well as protection of materials are growing fields of application of macro-organisms for biological control in Central Europe during the last 25 years.

Material destroying pests

Stored-product pests may destroy materials as well, either on their way to pupation sites or because the materials contain ingredients suitable for development. This initiated the interest in biological control of these pests in museums and other environments with cultural heritage items, as well as research in specific natural enemies of museum pests.

Spider beetles are mainly scavengers feeding equally on plant or animal materials. Beside their natural habitats, a number of species infest historic houses feeding on organic insulation materials and become a nuisance in residences (Howe, 1959). Moreover, spider beetles were found to infest historic books and herbaria (Gamalie, 2006). A number of spider beetle species were found to be suitable hosts for the larval parasitoid *Lariophagus distinguendus*, such as *Ptinus* spp. (Kaschef, 1955), *Gibbium psylloides* (Czenpinski, 1778) (Kaschef, 1961) and *Niptus hololeucus* (Faldermann, 1835) (Schöller and Prozell, 2011). Spider beetles are difficult to control in houses because the larvae develop hidden within walls and in dead floors, and no monitoring devices are available. In recent years, *L. distinguendus* was released against the hump beetle *G. psylloides* and the golden spider beetle *N. hololeucus* in Germany by pest control companies and became a regularly applied control technique (Kassel, 2008).

Larder beetles (Dermestidae) are among the cultural heritage pests most difficult to control by chemical means. Two approaches for biological control were tested so far, the control by a parasitoid naturally occurring in houses, and the control by a generalist predator transferred from the stored-product environment. The parasitoid *Laelius pedatus* (Say, 1836) (Hymenoptera: Bethylidae) is a gregarious ectoparasitoid of several larder beetle species including *A. verbasci* and *T. angustum*. The shiny black wasps measure 2 to 3 mm in length. During its life span a female wasp paralysed 74 ± 20 larvae of *A. verbasci* (Al-Kirshi, 1998). The average number of eggs per female wasp and day was 1.42 ± 0.2 if larvae of *T. angustum* were used as host. Most egg-laying activity was observed at temperatures between 25° and 28°C, while no oviposition occurs at 15°C. A mated female lives 6 to 8 weeks at room temperature (Al-Kirshi 1998). This parasitoid is occuring spontaneously in Central Europe in buildings, but there are not studies on the biological control potential of laboratory-reared wasps in field trials.

Stored product pests

Biological control in stored products is commercialized since 1998. Most applications were against stored-product moths in bakeries, food processing industries, retail trade and private households, and against weevils in grain on farms. Fifty percent of the types of application are control of pyralid