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Chilling Aeration to Control Pests and Maintain Grain Quality during In-Bin Storage of Wheat in Kansas

Abstract

Chilling aeration of stored grain is becoming very popular around the world since it offers many advantages in situations where ambient air conditions are not adequate to cool grain. It allows to cool grain, independent of ambient conditions, to “safe” temperatures where insect, fungi, and spoilage development is reduced to the minimum, and at the same time can potentially reduce chemical control use. The objective of this research was to evaluate the effectiveness of chilling aeration to preserve grain quality and control insect-pests. The research trial was developed from August to November 2015 in Central Kansas in two 1,270 metric tons (MT) steel bins with low-moisture wheat from the 2015 summer harvest. One bin was chilled and the other was used as a control (ambient aeration). Variables evaluated were: moisture content (MC), grain and flour quality, insect-pest development and reproduction rate, insect fragments per kg, and fungi presence. Chilling aeration cooled the grain in 135 hours to an average of 17°C, with minimum variation through the four months. Ambient aeration in the control bin cooled the grain to an average of 22°C after 308 hours, with variation over 16°C through the four months. Lower temperatures significantly diminished insect development and reproduction rate. Flour quality was better preserved in the chilled than in the control bin. There was no significant effect on MC, grain quality or fungi presence. The energy cost of running the grain chiller was 0.22 \$/MT more than the cost of ambient aeration in the control bin.

Keywords

Ambient aeration, chilling aeration, end-product quality, fungi, grain temperature, grain quality, insect-pests

Disciplines

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Comments

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Chilling Aeration to Control Pests and Maintain Grain Quality during In-Bin Storage of Wheat in Kansas

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ABSTRACT. *Chilling aeration of stored grain is becoming very popular around the world since it offers many advantages in situations where ambient air conditions are not adequate to cool grain. It allows to cool grain, independent of ambient conditions, to “safe” temperatures where insect, fungi, and spoilage development is reduced to the minimum, and at the same time can potentially reduce chemical control use. The objective of this research was to evaluate the effectiveness of chilling aeration to preserve grain quality and control insect-pests. The research trial was developed from August to November 2015 in Central Kansas in two 1,270 metric tons (MT) steel bins with low-moisture wheat from the 2015 summer harvest. One bin was chilled and the other was used as a control (ambient aeration). Variables evaluated were: moisture content (MC), grain and flour quality, insect-pest development and reproduction rate, insect fragments per kg, and fungi presence. Chilling aeration cooled the grain in 135 hours to an average of 17 °C, with minimum variation through the four months. Ambient aeration in the control bin cooled the grain to an average of 22 °C after 308 hours, with variation over 16 °C through the four months. Lower temperatures significantly diminished insect development and reproduction rate. Flour quality was better preserved in the chilled than in the control bin. There was no significant effect on MC, grain quality or fungi presence. The energy cost of running the grain chiller was 0.22 \$/MT more than the cost of ambient aeration in the control bin.*

Keywords. *Ambient aeration, chilling aeration, end-product quality, fungi, grain temperature, grain quality, insect-pests.*

Introduction

Aeration of stored grain is used to control grain temperature with the goal of preventing insect development, mold growth and maintain grain quality. Reducing grain temperature below 15°C soon after harvest reduces the need for chemical control of insect-pests and lowers the deterioration of grain by microorganisms (Navarro et al., 2002a).

In locations where ambient conditions limit the hours that are suitable for natural aeration, like sub-tropical climates or during summer harvest in the U.S., chilling aeration appears as a feasible option to lower grain temperature independent of ambient conditions. Grain chillers can be connected to storage bins through existing aeration fans and operate on three-phase power. Since grain is an excellent insulator, in typical Midwest locations, once a bin is cooled down, it will not need to be re-chilled before ambient aeration is needed in the late fall to lower grain temperatures further for storage through the winter and beyond.

Throughout the last five decades there have been several publications talking about the successful use of the grain chilling technology in Europe, Asia, Latin America, and the U.S. in crops like wheat, rice, and corn (Lazzari et al., 2010; Roskopf and Bartosik, 2009; Maier, 1997; Mason, 1997; Maier, 1994).

Lazzari et al. (2010) reported the use of chilling technology as part of a chemical-free program to store rice. In this research trial the grain temperature was successfully lowered between 12°C and 14°C, which helped to keep the grain free of external insects for eight months.

In Argentina, Roskopf and Bartosik (2009) used a grain chiller to lower the temperature of 1,200 MT of corn, from 24.3°C to 13.8°C in 104.5 hours.

In 1994, researchers at Purdue University developed and tested a prototype grain chiller to compare chilled aeration vs. ambient aeration in a commercial grain facility that stored popcorn in steel bins. The results showed significantly fewer Indianmeal moth (IMM) *Plodia interpunctella* in the chilled bins than in the conventionally managed bins. The chilling aeration also showed competitive usage costs compared to conventional aeration plus fumigation (Mason et al., 1997).

Based on field tests of chilling aeration in low-moisture wheat stored in Michigan, Maier (1992) simulated chilling in the Midwestern region of the U. S. The computer simulation showed that chilling aeration was capable of lowering the temperature of 579 MT of wheat from 30°C to 15°C in just one week. Continuous ambient aeration took 1.5 times longer than chilling aeration to cool the grain down to 10°C, which caused that the Dry matter losses (DML) were 63% to 67% times higher with the ambient aeration strategy than with the chilling aeration strategy.

The objective of this research trial was to evaluate the effectiveness of chilling aeration to preserve wheat quality and control insect pests during the summer and early fall in Kansas.

Materials and Methods

This research was developed in a Cooperative near Central Kansas from August to November 2015. The research trials were conducted in two 1,350 MT steel bins of 11.3 m in diameter and 20.7 m in height from the bottom to the top of the roof. In these bins there were two centrifugal fans, each with a 10 HP (7.5 kWh) motor. The fans were installed at the bottom of the bin in a parallel arrangement. Both bins were filled almost completely with hard red winter wheat (HRW) harvested in the summer of 2015 from several locations within a 24 km radius of the Cooperative. One of the bins was chilled (Chilled bin) and the other one was used as a treatment control bin (Control bin) managed by the Cooperative using their regular grain quality management strategies.

Grain Chiller Setup and Treated Bin Specifications

The grain chiller PCS-20 used in this project was facilitated by the Brazilian company CoolSeed (Paraná, Brazil). This equipment has the rated capacity to chill up to 150 MT per day in bins under 1,800 MT capacity.

The basic function of this equipment consists of a pair of cooling containers (circuits) where the cooling gas (refrigerant) is stored. When the unit is turned on, the cooling gas moves into a liquid state by means of exchanging heat with the ambient air around the cooling coils. Around the evaporator coils, the ambient air yields heat and the cooling gas moves from the liquid to the gaseous state, by removing sensitive and latent heat (moisture) from the ambient air. Before exiting the unit through the centrifugal fan and into the treated grain bin, the air is slightly reheated in the secondary reheating coils (evaporator) to lower the relative humidity (RH) to a level of about 70%. The rpm of the centrifugal fan adjusts itself according to the ambient temperature to achieve the set point temperature of approximately 10°C.

The grain chiller was connected to the transition parts of the grain bin through thermally insulated ducts of 0.4 m diameter as shown in Figure 1. To facilitate the entrance of the cooled air from the grain chiller into the treated bin, both aeration fans were removed. The plenum setup inside the bin consists of two internal ducts (one per inlet) going straight to about the center of the bin. Each internal duct has a square-shape perforated opening. The bin's roof has three outlet vents and two suction fans that occasionally worked during the length of the trials.



Figure 1. Grain chiller PCS-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.

Monitoring Air Conditions, Grain Temperature, and Moisture Content

Temperature cables (TSGC Inc., Spirit Lake, IA) of 18.3 m in length with thermocouples every 1.8 m were installed in three locations inside both the treated and control bins. The cables were located at approximately 2.7 m from the West, North and South walls of the bin. The temperature measured by each of the cables was recorded every hour using a wireless monitoring system model Grain TRAC (AgSense LLC., Hugson, SD).

Temperature and RH sensor type HOBOS (Onset, Bourne, MA) were placed in the fan transitions to record the temperature and RH of the air coming into the bins. Additionally, the HOBOS were also placed outside of the bins to record ambient conditions.

The wheat MC was measured using a GAC 2500-UGMA (Dickey John, Auburn, IL). Grain samples were taken with a vacuum probe next to each of the three temperature cables every 3 m in depth from the top of the grain mass to 9 m in depth. Samples were taken every 30 days from August 15th to November 20th, 2015.

Insect Pest Survival and Reproduction Rate Quantification

The effect of chilling aeration on the survival rates of the main insect pests was quantified using insect bioassays with the species Lesser Grain Borer (LGB) *Rhyzopertha dominica* and Red Flour Beetle (RFB) *Tribolium castaneum*. A bioassay of each species was located in the center of the bin 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. The same procedure was followed for both bins.

The bioassays consisted of plastic jars of 200 mL with holes on the bottom and top, and covered with wire mesh to prevent the insects from coming out of the jars and to allow circulation of chilled or ambient air. In each jar, 50 adults per species were placed inside, together with 80 g of wheat mixed with flour and broken kernels to make sure the insects would develop in ideal conditions.

After 28 days inside the bins the bioassays were taken out and all the adult live insects were quantified and taken out of the jars. The larvae, pupae and eggs (if any) were put back into the jars for progeny development quantification. Then, the jars were put in an incubator at approximately 27 °C and 30% RH with 16 hours of light and 8 of dark for another 28 days. Afterwards, the number of adult insects was counted again. This method was modified by the Stored-Product Entomology Laboratory of Kansas State University from the original version described by Chen et al. (2015).

Endemic Insect Population Sampling

Insect population inside the bins was 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. They were located in each bin in the North, South, East, West, and Center sections of the bins, approximately 1.5 m from the walls.

The insect probe traps were checked every 30 days from August to November. Insects inside the probe traps were identified (up to the genus level) and the adults of the main insect pests of stored products were counted.

Estimation of Potential Insect Fragments in Flour

A laboratory scale Entoleter designed by Finner and Singh (1983) and modified by the USDA-ARS Center for Grain and Animal Health Research (CGHAR), Manhattan, KS, was used to determine the number of insect fragments in the wheat samples (Brabec et al., 2015). The rpm of the Entoleter were adjusted to obtain between 2.5% and 3% of breakage.

The samples were taken from the top 3 m of the grain mass every 30 days from August to November. Each sample of approximately 500 g was taken next to each of the three temperature cables in each bin. Afterwards, each sample of three replicas of 500 g per sampling point were combined and reduced using a Boerner divider (Seedburo Equipment, Des Plaines, IL) to make a composite sample per sampling date.

After the passing through the Entoleter, the broken kernels were collected, sieved, and analyzed according to the procedure developed by Brabec et al. (2015) (fig. 2). The number of fragments per sample was related to the limit of 75 fragments per 50 g of flour established by the FDA. This was possible through the model developed by Brabec *et al.* (2015).



Figure 2. Insect fragments quantification from wheat samples using a laboratory scale Entoleter.

Mold Identification and Quantification

The effect of chilled aeration on stored product fungi was determined by quantifying the percentage of infected kernels in the stored wheat surface. Samples of 250 g were taken every 30 days from August to November from grain next to each of the three temperature cables in each bin at 16 m, 13 m, 10 m and 7 m of height in the grain mass, from bottom to top, using a pneumatic vacuum probe model Vac-A-Sample (Seedburo Equipment, Des Plaines, IL). The samples at the same height were combined in each sampling date.

Wheat samples were placed in Potato Dextrose Agar (PDA) and Maltose Dextrose Agar (MEA) medias. In each sampling date, three replicas (plates) per composite sample were analyzed for each bin. Each replica or plate consisted of 15 kernels previously disinfected with 2% hypochlorite sodium and immediately plated inside a sterile air-hood.

Afterwards, the plates were placed in an incubator at approximately 25°C and were checked 3 and 5 days later for the growth of *Fusarium*, *Aspergillus* or *Penicillium*. The results were presented in percentage out of the 15 kernels. This method was modified by the Grain Science Microbiology and Toxicology Laboratory from the original version described by Christensen and Meronouck (1986).

Statistical analysis was performed using the Minitab statistical software (Minitab Inc., State College PA). Statistically significant differences were analyzed with Tukeys test ($p < 0.05$).

Grain Quality Analysis

Grain quality was determined before and after the treatment period with the chilling aeration on August and on September by obtaining samples of 1,350 g of wheat using the same method and equipment used for the sampling of grain for mold identification and quantification.

All the samples from Chilled and Control bins were combined to obtain a composite sample of approximately 2,500 g for each bin. The wheat grading procedure for MC, test weight, dockage, foreign material, damage, shrunken and broken, insect damaged kernels (IDK), and total defects was performed by the Kansas Grain Inspection Service (KGIS) in Topeka, KS.

Flour Quality Analysis

Sampling for flour quality was done in the same way as the grain quality sampling except that the composite samples of 900 g were collected per cable, which means that for each bin there were three samples before chilling (August) and three samples after chilling (September). The sample from each cable was considered a repetition for the calculation of significant differences between sampling dates.

Samples were analyzed to quantify flour quality in the Wheat Quality Lab (WQL) of Kansas State University. The variables analyzed were: MC and protein content (DA7200 NIR, Perten Instrument) and baking quality (AACC 10-10.03). For the baking quality analysis, all the samples were tempered to 15% before milling and then ran through a mixograph (National Manufacturing Co., Lincoln, NE) before baking in order to estimate mixing time.

Statistical analysis was performed using the Minitab statistical software (Minitab Inc., State College PA). Statistically significant differences were analyzed with Tukeys test ($p < 0.05$).

Cost Analysis of Ambient and Chilling Aeration

The energy consumption used during the chilling treatment was measured using a kWh counter that was installed at the entrance of the power inlet of the chiller.

The energy consumed during the ambient aeration in the Control bin was calculated according to the hours of operation reported by the Wakefield Cooperative.

The costs of the ambient and chilling aeration process were calculated based on the energy consumption, using an average cost of 0.084 \$/kWh (obtained from local electrical service provider), and taking into account additional charges for basic service and consumption fees.

Results and Discussion

Ambient and Chilling Aeration

The chilling period spanned discontinuously from August 22nd to September 14th, 2015, for a total of 314 hours of active chilling. The temperature front reached the top of the grain mass much sooner than the 314 hours, but due to technical difficulties with the grain chiller during certain periods, the equipment was left running until the 314 hours were reached to test its capacity.

The average temperature and RH of the chilled air going into the bin was 15^oC and 72.1%, respectively (fig. 3). These conditions allowed temperatures below 17^oC to be achieved in the top grain layer of the chilled bin 52 days before they reached this level in the control bin by aeration with ambient air (fig. 4).

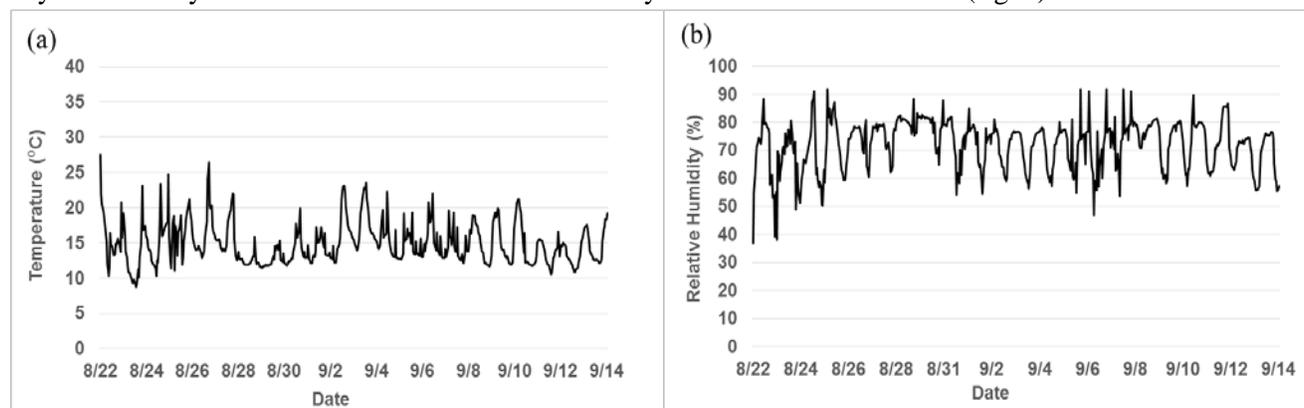


Figure 3. Chilling (a) temperature and (b) relative humidity going into the Chilled bin from Aug. 22nd to Sep. 14th, 2015.

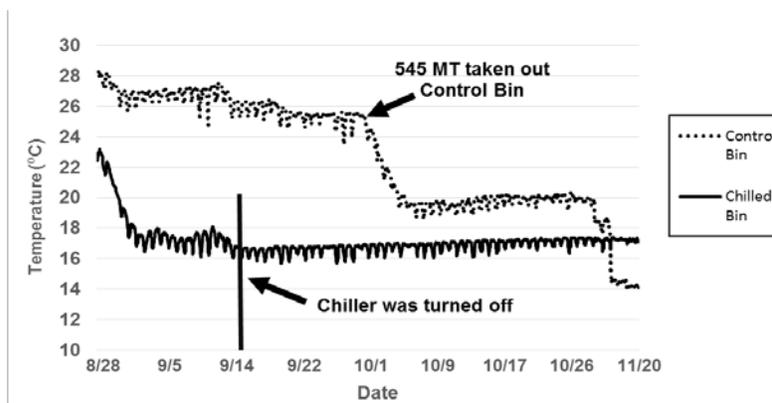


Figure 4. Average grain temperature in the Control and Chilled bin from Aug. 28th to Nov. 20th, 2015.

The grain chiller was setup to work at 10^oC, but according to data collected in the air inlet of the bin, the average temperature of the air introduced into the Chilled bin was 5^oC over the set point, and showed significant fluctuations in temperature (9^oC to 28^oC) and RH (37% to 91%) during the trial (fig. 3). This could be explained by the intermittent power downs suffered during the trial caused by the malfunction of a thermostat controller, which was supposed to prevent the temperature to drop below a certain point to avoid the freezing of the evaporator and subsequent shutdown.

The automatic control program of the grain chiller also adjusted the fan speed according to the ambient temperature, in order to deliver the set temperature. The average airflow coming from the grain chiller into the treated bin was of 0.06 m³/min/t, with 0.08 m³/min/t and 0.04 m³/min/t, as maximum and minimum values, respectively. The colder air temperature front reached the top of the bin on September 2nd after 135 hours of treatment. Once the temperature front reached the top of the bin, the temperature throughout the grain mass stabilized at approximately 17^oC. The fluctuations of the air coming out of the chiller due to the thermostat

malfunction may have prevented the temperature to drop even lower.

From the time the grain chiller was turned off on September 14th (which is indicated by a vertical line in Figure 4) to November 20th, the average grain temperature inside the chilled bin was 17^oC, with a minimum of 11^oC and a maximum of 19^oC. This demonstrates that the chilling aeration was effective to keep a uniform temperature throughout the grain mass, which lowered the risk of temperature and consequently moisture migration that could decrease the quality of grain (Navarro et al., 2002a).

From August 22nd to November 20th the average ambient air temperature was 17^oC, with a minimum of -3.3^oC and a maximum of 37^oC (fig. 5a). The average ambient air RH was 60%, with a minimum of 13% and maximum of 93% (fig. 5b).

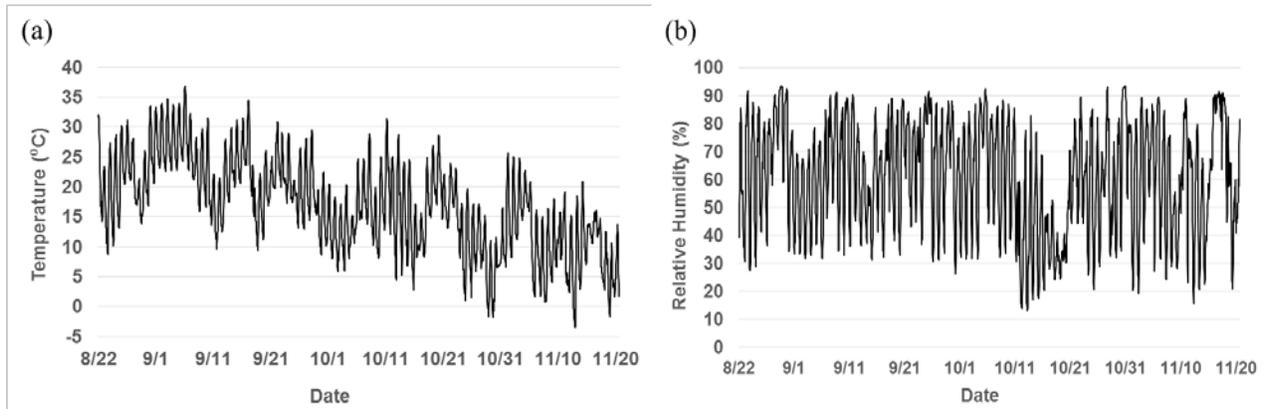


Figure 5. Ambient air (a) temperature and (b) relative humidity in Central Kansas from Aug. 22nd to Nov. 20th, 2015.

Using their own criteria, the Farmer’s Coop management turned on the aeration fans on the Control bin from August 24th to October 5th when they considered the ambient air temperature and RH appropriate for aeration. Figure 6 shows the temperature and RH conditions of the air coming into the Control bin in each of the aeration runs. The total active aeration time was of 308 hours at an average airflow of 0.1 m³/min/t. The average temperature of the air going into the bin was 23^oC, ranging from 10^oC to 34^oC (fig. 6a). The average RH was 50%, with a minimum of 16% and a maximum of 94% (fig. 6b).

The first aeration run was performed from August 24th to the 30th. During this period the fans were turned on late in the afternoon and turned off the next day in the late morning.

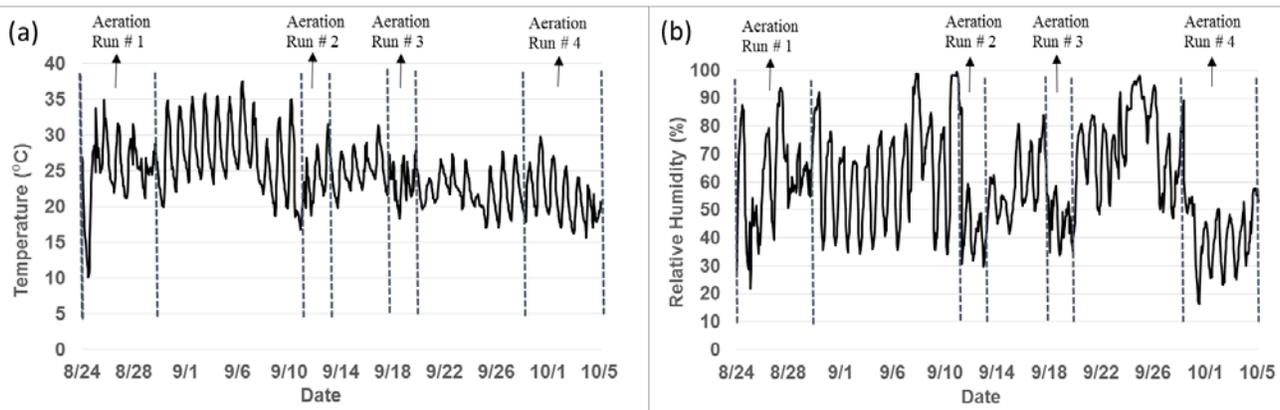


Figure 6. Air (a) temperature and (b) relative humidity going into the Control bin from Aug. 24th to Oct. 5th, 2015.

As it can be observed in Figure 4, the first set aeration run performed in August was not effective enough to lower the temperature below 24^oC. The second and third set of aeration runs from September 11th to 13th, and from September 18th to 20th, lowered the temperature of the lower layers of the grain mass. Nevertheless, the aeration time was not enough for the temperature front to reach the top of the grain mass, which left the upper

layers of the grain mass with temperatures over 24°C for most of the summer. The last aeration run was from September 29th to October 5th, which coincided with the time when unexpectedly 545 MT were taken out of the bin, which also helped to lower the grain temperature (thermal insulation effect decreased). From there on, the temperature of the grain remained low (below 21°C) since by this point the ambient temperature had dropped to an average 13°C (fig. 5a).

The MC of the grain inside the Chilled bin was fairly uniform throughout the grain mass and the storage time (11.1% - 11.8%) which means that the chilling treatment did not cause any drying or rewetting. There was no noticeable effect of the ambient aeration in the Control bin either.

Effect of Chilling Aeration on Insect Survival and Reproduction

The bioassays of LGB and RFB were taken out of the two bins and the fan transition part after 28 days. The percentage of live adult insects found, out of the original 50, are shown in Table 1. The average temperature in the fan transition and the grain surface of the Chilled bin during the 28 days was 17°C and 19°C, respectively. These temperatures are not lethal for the insects, but they do stop the development and slow the oviposition and larvae growth (Navarro et al., 2002).

Table 1. Percentage of live adult insects out of 50 original adults (first generation) of LGB and RFB after 28 days inside the Chilled and Control bin and number of adults (progeny) that develop after 28 days in incubation at 27°C and 30% RH.

	Bin	LGB		RFB	
		0.3 m below grain surface	Fan Transition	0.3 m below grain surface	Fan Transition
First Generation (% Live Insects)	Chilled	82±5	91	91±5	89
	Control	79±27	85	93±10	86
Progeny (# Adults)	Chilled	4±1	4	3±2	2
	Control	968±65	772	16±5	14

In the Control bin the temperature of the fan transition and the grain surface were 25°C and 27°C, respectively. The optimum development temperatures for LGB and RFB are between 32°C and 35°C. Outside of this range the development from egg to adult would take more than 24 days (Navarro et al., 2002). This would explain why there was no significant increase of the population of these two species in the Control bin in the first 28 days, although the temperatures were higher than in the Chilled bin.

Although there was no noticeable difference in the adult count in the first generation, a large difference was observed on the number of larvae and pupae, which was higher in the Control than in the Chilled bin. The average adult count in the progeny for LGB in the Control bin was 968 and 772 in the grain surface and the fan transition part, respectively. An average adult count of four resulted in the Chilled bin's fan transition part and grain surface (Table 2). These results show that the low temperatures in the Chilled bin had a significant effect in the oviposition and fecundity rate of this species. Navarro et al. (2002) observed that at 25°C a female LGB can lay between 52 and 561 eggs over a period of 11 to 38 days.

In general, temperatures between 17°C and 22°C, like the ones in the chilled bin, are considered "safe" for insect control management since the life cycle usually takes three months or more, and the oviposition and fecundity slows down to a point where population growth is almost insignificant (Navarro et al., 2002a).

The results of the second progeny regarding RFB also showed differences, although they were not as different in absolute numbers as the ones observed in LGB. It seems that due to the low RH (30%) that the insects were incubated in the laboratory affected this species more than LGB, and delayed the larval and pupae development into adults.

Insect Population in the Chilled and Control Bin

The main insect-pests found in the probe traps of both bins were: rusty grain beetle (RGB) *Cryptolestes* spp.,

red flour beetle (RFB) *Tribolium* spp., sawtoothed grain beetle (STB) *Oryzaephilus* spp. and maize weevil (MW) *Sitophilus* spp.

The probe traps located in the center of the bins were where the highest concentrations of insect populations for all the species mentioned in every sampling date (table 2). The reason for this distribution could be the concentration of fine, chaff, and broken pieces of grain in the central core of the bins since no “coring” or leveling of the center core had been done. Insects that can’t feed from sound grain (secondary pests) often develop perfectly in this kind of material (Navarro *et al.*, 2002).

Table 2. Number of adult insects found in the probe traps located in the center of the Chilled and Control bins collected on Aug. 15th to Nov. 20th, 2015.

Bin	Insect Species	Sampling Date			
		August	September	October	November
Chilled	RGB	15	27	-	12
	RFB	0	27	-	21
	STB	0	10	-	0
	MW	0	0	-	13
Control	RGB	28	1370	-	1000
	RFB	0	544	-	91
	STB	0	2	-	0
	MW	0	0	-	0

On the first sampling date the number of insects were quite low in both bins, probably because this grain was recently harvested in the months of June and July. The most common genus was RGB. This species is able to survive in cracks and crevices, feeding from the residues of previous harvest before the new loading of grain (Reichmut *et al.*, 2007). This could have given it an advantage over other species and made it able to survive in the residues of the previous harvest.

On the second sampling on September 22nd (after chilling treatment) the population growth of all four genus was considerably suppressed in the Chilled bin, which clearly shows that the average temperature of 17^oC (fig. 4) slowed down the development of the main insect pests present in this bins. The predominant genus found were RFB and RGB, with 27 adults of each. Subramanyam and Hagstrum (1996) reported that a female of RGB can produce around 200 eggs during their lifetime, therefore it could be said that between the first and second sampling there was practically no oviposition or larval growth in the Chilled bin.

In the Control bin, 544 and 1370 adult insects of RFB and RGB, respectively, were collected from the center core probe trap on this date (table 2). This was a considerable increase of the population size in just 37 days, which shows the importance of cooling the grain as fast as possible once it is in the bin. Hagstrum and Subramanyam (2006) determined that for every month that cooling is delayed populations of insects would grow 5- to 25-fold their original size. During this period the average temperature in the Control bin was of 27^oC.

During the month of October the probe traps in the Control bin had to be taken out due to the unloading of grain, reason why there are no results for this month. In the November sampling, a clear difference in insect development was still noticeable, even though the temperature in the Control bin had decreased to 14^oC due to the movement of grain that diminished the insulation effect and normal reduction of the ambient temperature due to the start of the fall season. There was no noticeable change in the temperature in the Chilled bin (fig. 4).

An increase of the population of MW was observed in the Chilled bin in the sampling of November. This sudden appearance could be explained due to the start of the maize harvest season which would normally attract MW since they are very good flyers and are known for infesting neighboring commodities and being tolerant to low temperatures (Navarro *et al.*, 2002). Although the insect was present, the results of insect fragments (table 3) indicate that it wasn’t feeding or reproducing inside the bin. This means that the infestation of MW wasn’t created inside the bin and since the development rate of this species would take more than 220 days at

temperatures as low as 15°C (Rees, 1996), it is unlikely that an infestation of MW would develop inside the Chilled bin, despite of its presence inside the bin. RGB was the predominant genus found in the Control bin, with numbers as high as 1000 in the center core of the grain mass.

Calculation of Insect Fragments

The results of the laboratory Entoleter were below 0.5 insect fragments in total per 500 g of grain in both bins and during all sampling dates (table 3), which would be below the FDA action limit of 75 flour-frags per 50 g of flour according to the prediction model developed by Brabec et al. (2015).

Table 3 Average number of insect fragments found per 500 g of wheat in the Chilled and Control bins.

Bin	Insect Fragments per kg of grain			
	August	September	October	November
Chilled	0 ^A	0.3 ^{Aa}	0.3 ^{Aa}	0.1 ^{Aa}
Control	0 ^A	0.4 ^{Aa}	0.4 ^{Aa}	0.4 ^{Aa}

(^A) Mean values with the same letters within the same bin but at different sampling dates are not significantly different by Tukeys test ($p > 0.05$).

(^a) Means values with the same lowercase letters within the same sampling date but at different bins are not significantly different by Tukeys test ($p > 0.05$).

A great variability was observed in the number of insect fragments found in each of the 500 g samples collected from both bins, probably due to the low count of internally infested kernels. Brabec et al. (2015) found that on average, each kernel infested by a weevil contributed to 1.4 to 2.2 piece counts, which meant that if only one insect was found among the three replicas, it had a big influence in the calculus of the standard deviation, and in fact this was the case in most of the samples since the population of weevils or internally-infesting insects was almost inexistent.

These results seem contradictory due to the almost inexistent population of weevils according to the probe traps in the Control bin and the increase of MW in the Chilled bin in the last sampling date. This can be explained by the differences in sampling between using probe traps and grain probing, where the probe traps are exposed for a longer period of time in the grain mas compared to the short time of just probing the grain. While it is more likely that a higher number of insects are found in the probe traps than in the grain samples, the correlation between both methods is dependent on many variables like interaction among different species, spatial patterns of insect populations, number and size of grain samples, location of traps in the grain mass, temperature of the grain mass, among others (Athanasidou and Buchelos, 2000).

Mold Identification and Quantification

The results of the two medias used for this analysis were practically identical for which only the results of the PDA are presented in this section.

The most common fungi detected in the mold tests during all sampling dates and at every grain height sampled in both bins was *Fusarium* spp. (table 4). It is likely that the presence of *Fusarium* spp. in the sampled grain came from the field and did not develop inside the bins since it is a more common field fungi than *Aspergillus* spp. and *Penicillium* spp. and it requires higher ERH and EMC to germinate and develop (Navarro et al, 2002a).

According to the Wheat Quality Annual report, the 2015 harvest in Kansas was heavily hit by rain, drought and diseases (Hilderbrand, 2015). The results of the grain quality analysis confirmed it (table 5). Most of the damage observed in wheat from both bins was due to fungi in the form of “scab” which is caused by *F. roseum*. The “scab” is characterized by shriveled and reddish discolored kernels that sometimes are friable with a chalky interior (Christensen and Meronouck, 1986). Since this fungi requires high RH to develop, the presence of this mold inside the bins did not seem to have increased throughout the four months of monitoring the quality.

Table 4. Percentage of kernels in PDA media infected by *Fusarium* spp., *Aspergillus* spp., or *Penicillium* spp. in the different layers of the Chilled and Control bins from samples taken during in the August, September, October and November, 2015.

Sampling Date	Height (m)	Kernels infected (%)					
		Chilled Bin			Control Bin		
		<i>Fusarium</i> spp.	<i>Aspergillus</i> spp.	<i>Penicillium</i> spp.	<i>Fusarium</i> spp.	<i>Aspergillus</i> spp.	<i>Penicillium</i> spp.
August	16	9.5 ^a	0	0	4.4 ^a	0	0
	13	18.37 ^a	0	0	13.93 ^a	0	0
	10	13.3 ^a	0	0	18.57 ^a	0	0
	7	16.97 ^a	0	0	8.77 ^a	0	0
	Average	14.53 ^{*A}	0	0	11.42 ^{*A}	0.0 ^A	0
September	16	0.0 ^a	0	0	0.0 ^a	6.67 ^b	0
	13	8.9 ^a	0	0	2.23 ^a	0.0 ^a	0
	10	6.67 ^a	0	0	8.87 ^a	0.0 ^a	0
	7	0.0 ^a	0	0	8.9 ^a	0.0 ^a	0
	Average	3.89 ^{*A}	0.0 [*]	0	5.0 ^{*A}	1.68 ^{*A}	0
October	16	6.67 ^a	0	0	-	-	-
	13	6.67 ^a	0	0	-	-	-
	10	2.23 ^a	0	0	-	-	-
	7	0.0 ^a	0	0	4.47	0	0
	Average	3.89 ^{*A}	0	0	4.47 ^{*A}	0.0 ^A	0
November	16	0.0 ^a	0	0	-	-	-
	13	44.43 ^b	0	0	-	-	-
	10	2.23 ^a	0	0	-	-	-
	7	0.0 ^a	0	0	0	0	0
	Average	11.67 ^{*A}	0	0	0.0 ^{*A}	0.0 ^A	0

^(a,b) Mean values with the same letter within the same bin and sampling date but at different heights of the grain mass are not significantly different by Tukeys test ($p > 0.05$).

^(*) Mean values with the same symbol in the bin's average within the same sampling date but at different bins are not significantly different by Tukeys test ($p > 0.05$).

^(A) Mean values with the same letter in the bin average within the same bin but at different sampling dates are not significantly different by Tukeys test ($p > 0.05$).

Although microfloral growth is mostly dependent of ambient relative humidity, low temperatures like the ones found in the Chilled bin would be adequate to limit the damage caused by fungi, even at MCs higher than 13% and for up to a year, but if the temperature is maintained between 8^oC and 10^oC (Christensen and Kaufmann, 1974).

Aspergillus spp. only appeared in the top layer of the Control bin in the samples taken on September 22nd. Although it was not possible of keep track of the presence of this mold in the top layer since the grain had been moved by the next sampling, it is very unlikely that there had been any development of this mold since the average MC of the grain was below the optimum development range of *Aspergillus* spp. (13.5% to 17%) (Navarro *et al*, 2002a). There was no detection of *Penicillium* spp. in any sample from neither of the bins at any sampling date or quantity with any of the two medias.

Grain Quality Evaluation

The grain quality results indicate that there was no change in grade from before and after the chilling treatment (table 5). The difference in the quality values observed in the parameters evaluated in the samples of both bins are considered normal according to the experts of KGIS.

Table 5. Grain quality analysis of wheat stored in the Chilled and Control bins from samples taken before chilling (Aug. 15th) and after chilling (Sep. 22nd).

Bin	Sampling date	MC (%)	Test Weight (kg/m ³)	Dockage (%)	Foreign material (%)	Damage (%)	Shrunken & Broken (%)	Insect Damaged Kernels (#)	Total Defects (%)	Grade
Chilled	August	11.4	78.6	0.5	0.1	0.7	0.3	1	1.1	1
	September	11.3	79.7	0.3	0.2	1.3	0.7	1	2.2	1
Control	August	11.4	78.9	0.4	0.3	0.8	1	0	2.1	1
	September	11.2	78.9	0.4	0.3	0.4	0.9	0	1.6	1

It can be observed in Table 5 that the most influential factor in the Total Defects parameter quantified with grain grading in the Chilled bin was the damage caused mainly by fungi (Damage). As it was observed in Table 4, the “scab” damage was quite common in both bins for the conditions in which this wheat was harvested. Nevertheless, this damage did not affect the overall quality after harvest due to the low MC of the grain.

In the Control bin the most influential factor in Total Defects parameter were the Shrunken & Broken. This factor plus the temperatures present in this bin would explain the high populations of secondary pests, since these insects can't feed from the whole grain (Rees, 1996).

For Insect Damaged Kernels (IDK), one kernel was found in samples from each sampling dates that were affected by internal feeding insects. This could mean that this damage could have happened in the field since no primary pests were observed during the first sampling date in either the probe traps or the grain samples (table 2 and 3).

In general, it should be mentioned that, despite the conditions that this harvest had to endure, the wheat stored in these bins was graded as U.S #1. Navarro *et al.* (2002) mentions that the rate of deterioration during storage depends on initial condition of the grain, MC, and temperature. So, although the storage temperatures were quite different in the two bins, the initial quality and MC were good enough to mask the temperature on overall quality.

Flour Quality Evaluation

The flour quality analysis did not show changes in the characteristics of wheat after the chilling treatment that would affect end-use product quality (table 6). This shows that lower temperatures during storage help preserve the quality of wheat. These results are similar to the ones found by Mhiko (2012) in which wheat was stored for five months at different temperatures and the grain stored at 15°C and 60% RH presented the least quality deterioration.

Table 6. Flour quality analysis of wheat stored in the Chilled and Control bins from samples taken before chilling (Aug. 15th) and after chilling (Sep. 22nd).

Variables	Chilled Bin		Control Bin	
	August	September	August	September
MC Wheat (%)	10.53 ^a	10.41 ^a	10.39 ^a	10.28 ^a
Wheat Protein (%)	12.49 ^a	12.40 ^a	13.33 ^a	12.59 ^a
Flour Protein (%)	11.14 ^a	10.97 ^a	11.87 ^b	11.27 ^a
Absorption (%)	63.83 ^a	64.33 ^a	64.69 ^a	65.33 ^a
Mix Time (min)	3.73 ^a	3.42 ^a	3.53 ^b	3.00 ^a
Loaf Volume (cc)	741.08 ^a	814.33 ^a	818.34 ^b	767.00 ^a

(^{a,b}) Mean values with the same letter within the same bin and quality variable but at different sampling dates are not significantly different by Tukeys test ($p > 0.05$).

Although the changes in loaf volume were not statistically different in the Chilled bin, it can be observed that there was a slight increase in volume from samples taken after the first month of storage at approximately 17°C. Lower temperatures during storage tend to show an increase in dough extensibility, independently of the RH (Gonzalez-Torralba, 2013).

In the Control bin there was a significant decrease in quality after 38 days storage period. It is observed that protein content decreased from 11.87% to 11.27%. Mixing time also decreased from 3.53 to 3 minutes, as well as loaf volume decreased from 818.34 cc to 767 cc.

Gonzalez-Torralba (2013) observed that at temperatures of approximately 30°C during storage, dough extensibility decreased while tenacity and strength increased due to enhanced oxidation of thiol to disulfide groups. This has a negative impact in loaf volume and crumb softness (Gras et al., 2001).

The change of protein content in the flour produced from the wheat taken out of the Control bin could be explained by the higher temperatures during storage that increase the proteolytic activity in the wheat, which causes that the endo- and exopeptidases break the polypeptide bonds into simple peptide chains and decrease the protein content (Mhiko, 2012).

Although the deterioration of protein during storage has been observed in other research trials, most of them have observed significant changes after more than one month of storage (Kibar, 2014; Mhiko, 2012). This could indicate that the changes in protein content in the samples could have been due to sampling or processing errors, nevertheless this can only be proven by extending the chilling trial during a wider storage period.

Power Consumption and Costa Analysis

The grain chiller worked in average on a 28 kWh load from August 22nd to September 14th, 2015. To calculate this power load, it was taken into account the consumption of the chiller's centrifugal fan, two axial fans and its two compressors. The two centrifugal fans of the Control bin worked on 7.5 kWh load from August 24th to October 5th, 2015. During the chilling trial, there was a total power consumption of 8,794 kW for the 314 hours the chiller was running which resulted in an electrical cost of 1.93 \$/kWh using a kWh average cost for the Central Kansas region of 0.084 \$/kWh. In the Control bin, the centrifugal fans ran for 308 hours for a total power consumption of 4,620 kW, which resulted in an electrical cost of 1.03 \$/kWh. The difference in cost between ambient and chilled aeration was 0.22 \$/MT (table 7).

Table 7. Power consumption (kWh) and cost per hour (\$/hr) and metric tonne (\$/MT) for running chilling and ambient aeration.

Bin	Average Load (kWh)	Hours of operation	Total energy (kW) consumption	\$/hour	\$/MT
Chilled	28	314	8794	1.93	0.45
Control	7.5	308	4620	1.04	0.23

^aAverage load of system: 1 centrifugal fan of 7.5 kW+ 2 axial fans of 950 W/ea+ 2 compressors of 9.325 kW/ea.

^bCalculated according to the consumption of the two centrifugal fans connected to the Control bin.

^cBased on an average cost of 0.084 \$/kWh

The cost of the chilling aeration nearly doubled that of ambient aeration, nevertheless it has to be taken into consideration that the temperature of the Chilled bin was lowered and stabilized throughout the grain mass at 17°C after only 135 hours, but it was left running until the 314 hours to test its capacity. It also has to be noted that the chilling treatment was more effective to control the population growth of insect-pests, as it was shown in the results of the insect sampling and bioassays. The chilling treatment was also better to preserve some of the quality parameters of the end-product like loaf volume, as it was shown in the results of flour quality. Taking into consideration these results, chilling aeration would be highly competitive, compared to ambient aeration, in a market that will pay for high quality end-product in regards to flour quality and baking needs or even in one that

will pay more for chemical-free grain.

Although there was no fumigation during the present research trial, according to an economic computer model developed by Rulon et al. (1999), a management strategy based on chilling aeration would lower the exposure of a elevator business to changes in input price levels, such as fumigation materials and labor, and would also be highly competitive in market where premium quality or pesticide-free wheat is demanded.

Conclusions

The PCS-20 grain chiller was capable of lowering the temperature of the 1,350 MT from approximately 28°C down to 17°C in approximately 135 hours, without modifying the MC. This rapid cooling of the grain inside the treated bin slowed down the reproduction rate of the main insect pests that were present inside the bin.

According to the mold analysis, the chilling aeration treatment had no effect on the mold growth. Neither was there an effect of the chilling treatment on the quality and grade of the wheat since no difference was observed compared to the quality and grade of the wheat in the Control bin which was treated with ambient aeration according to the strategy developed by the Farmer's Cooperative.

The results of the flour quality analysis demonstrated that loaf volume characteristics were better preserved with the chilling aeration strategy than with the ambient aeration.

The cost analysis, based only on the power consumption of both aeration strategies, showed that the chilling aeration strategy was 0.22 \$/MT more expensive than the ambient aeration strategy developed by the Cooperative.

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