Directional Flow of Summer Aeration to Manage Insect Pests in Stored Wheat

F. H. Arthur, M. E. Casada

Abstract. *Field trials were conducted in metal wheat storage bins to determine whether pressure aeration, pushing ambient air from the bottom, or suction aeration, pulling air down from the top, would be more efficient at cooling the wheat mass and thereby limiting insect population growth. Aeration was accomplished at an approximate airflow rate of 0.22 to 0.31 m^3/min/t and was done by adjusting thermostatic controllers to operate the aeration fans when ambient temperatures fell below specified thresholds. Summer and autumn cooling cycles using suction aeration cooled the warmest part of the bin, the top of the grain mass first, which resulted in lower overall wheat mass temperatures compared to pressure aeration, where the top of the grain mass always remained warmer than with suction aeration. This cooling effect was most pronounced in the upper surface of the grain mass, and insect pest populations as measured by pitfall traps were consistently less in bins with suction versus pressure aeration. Results seem to indicate that suction aeration would be more beneficial than pressure aeration for controlling insect pests in wheat stored in the southern plains of the United States.*

Keywords. *Aeration, Insects, Temperature, Control, Wheat.*

Aeration, which is generally considered as the use of ambient air to cool a grain mass, can be an important component of integrated insect pest management programs for wheat stored in the south-central United States (Hagstrum et al., 1999), primarily Kansas, Oklahoma, Texas, southern Nebraska and eastern portions of New Mexico and Colorado, ranging from about 30° to 40° north latitude. This process utilizes low-volume airflow rates of about 0.055 to 0.33 m^3/min/t (0.05 to 0.3 cfm/bu) differing from drying of grain, which generally involves airflow rates that are at least one order of magnitude greater than what is used for aeration (Harner and Hagstrum, 1990). A common threshold for an adequate air temperature for aeration is 15°C, which is the lower temperature limit of development for most stored-product insect pests (Howe, 1965; Fields, 1992).

If ambient temperatures are at or near this threshold at the time of harvest and grain storage, aeration can quickly cool a grain mass and immediately limit insect population development. However, in much of the south central and southern plains of the United States, wheat is harvested and placed in storage during June and July, and temperatures during these summer months can be conducive to rapid insect population growth and spread. However, there have been several field trials (Reed and Harner, 1998a,b; Casada et al., 2002; Arthur and Casada, 2005) and modeling simulation studies (Flinn et al., 1997; Arthur and Flinn, 2000) showing that an initial summer cooling cycle cooling to a level of about 24°C, followed by second cooling to 15°C in early autumn, severely limits insect population growth in stored wheat. Summer aeration in the south central and southern plains of the United States exploits air from the coolest part of the day to attain adequate cooling by using an automatic controller to turn on the aeration fan when ambient temperatures decrease below the desired temperature threshold at night. Latent heating, which results from high humidity at night, limits the available hours at night with satisfactory cooling temperatures. When air with an equilibrium moisture content higher than the grain moisture content flows through the grain mass the grain absorbs moisture from the air and the latent heat from that condensing moisture is also adsorbed, raising the grain temperature higher than the ambient air temperature. However, much of the region, including all of Kansas, has sufficient hours to produce a summer cooling cycle with adequate aeration fan sizes (Akdogan and Casada, 2006).

Insect pest infestations often originate in the upper surface of the grain mass and then slowly spread downward (Vela-Coiffier et al., 1987; Hagstrum, 1987, 1989, and 2001). Although infestations can originate through the bottom portion of a grain mass, or from residual infestations within a grain bin or silo (Reed et al. 2003; Arthur et al., 2006), insect immigration into the bins through flight can cause infestations to be concentrated in the top portion of a grain mass. Therefore, insect sampling and monitoring programs utilizing pitfall traps can indicate the presence and abundance of particular species, and can be used to assess the effects of aeration on population development (Vela-Coffier et al., 1987; Reed et al., 1991; Hagstrum et al., 1998). Temperatures recorded inside the grain mass through the use of sensors or data loggers can also be used to assess the benefits of aeration, and to relate the decreases in tempera-

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ture provided by aeration to insect population development (Ranali et al., 2002; Arthur and Casada, 2005; Arthur et al., 2008).

Although the benefits of summer aeration in stored wheat have been demonstrated, there has been relatively little research regarding the effects of directional airflow on either grain temperature or on insect population development. Therefore, the objective of this study was to determine if pressure aeration, which is pushing air up through the bottom of a grain mass, or suction aeration in which air is pulled downward through the grain mass, would be more beneficial for stored wheat insect control.

Materials and Methods

This study was conducted in six metal bins located at the USDA-ARS Center for Grain and Animal Health Research (GGHAR), Manhattan, Kansas. These bins had perforated floors and were 3.7 m in diameter with a 4.6-m sidewall height with a conical roof 6.2 m high at the peak, with a total capacity of about 32 t of wheat (1,250 bushels). The first trial was conducted from 20 July 2004 though 4 March 2005, using wheat harvested in the 2004 crop. Wheat was received at the research elevator at the CGHAR in mid-June and held in the elevator until it was transferred into the bins. Grain was transferred with a grain truck with an opening in the tailgate, and the wheat was dumped onto an auger and loaded into the bin. After each bin was filled to a depth of 3.8 m (31.0 t of wheat) and leveled, a series of HOBO data loggers (Onset Computers, Bourne, Mass.), with cables inserted at approximate depths of 0.3, 0.9, and 1.8 m from the top surface of the wheat mass, were installed in each bin at the center and at the north and south positions, approximately 0.6 m from the bin wall. The cables were pushed down through the wheat mass using a notched metal flange, which was attached to a grain trier (Seedboro Equipment, Des Plaines, Ill.), to hold each cable in place as it was inserted down into the wheat.

Three bins were randomly assigned to receive pressure aeration (pushed up from the bottom) and three were assigned suction aeration (air pulled from the top), at an approximate airflow rate of 0.22 m^3/min/t (0.2 cfm/bu). The airflow rate was measured near the fan inlet (pressure systems) or outlet (suction systems) using a calibrated vane anemometer inside a 0.9-m long × 15-cm inside diameter pipe attached to each aeration fan. Airflow rate was controlled with a slide gate mounted on the aeration pipe. For each aeration system the air velocity was adjusted to give 0.22 m^3/min/t ±5%. A temperature controller was already installed on the aeration system on each bin, and could be set so that the fans would operate when temperature fell below a specified threshold. The process of loading all bins and inserting the cables took about a week to complete, and on 20 July the test was initiated by activating the aeration set point at about 24°C; the fans operated only when outside ambient temperature at the controller sensor fell below this threshold.

Insect populations inside each bin were sampled using standard plastic pitfall traps (Trécé Corporation, West Adair, Okla.). These traps are approximately 46 cm long, with openings in the side, and a plastic tip on the bottom. The insects enter the trap through these side openings and collect in the bottom. On 29 July, one trap was placed just below the surface of the wheat mass, at the north, south, east, west, and center positions of each bin, and were held in the wheat for one week. After this time, the traps were collected, and the insects were sampled and identified to species. Upon initial sampling, the insects were identified as one of seven species: *Cryptolestes ferrugineus* (Stephens), the rusty grain beetle; *Ahasversus advena*, the foreign grain beetle; *Typhaea stercoria*, (L.), the hairy fungus beetle; *Tribolium castaneum* (Herbst), the red flour beetle; *Oryzaephilus surinamensis* (L.), the sawtoothed grain beetle; *Sitophilus oryzae* (L.), the rice weevil; and *Rhyzopertha dominica* (Fab.), the lesser grain borer. This sampling process was repeated on 27 August, 9 September, 14 October, and 15 November.

Temperature records were collected every two weeks until the study was concluded on 4 March 2005. The sensors and/or cables occasionally failed to operate and gave spurious readings that had to be deleted from the data set (relatively rare readings that were far outside the bounds of other temperatures in the bins). In a previous experiment, all temperature records from a particular treatment were combined into average values and reported as those values (Arthur and Casada, 2005). Similarly, because of extreme variation in insect collection data, all data from each bin were combined for a particular species and date and the data analyzed through Chi-Square analysis (Arthur and Casada, 2005) on the total number of insects of each species collected from the three bins with pressure aeration and the three bins with suction aeration.

The experiment was repeated during the 2006-2007 grain storage season. It was not done in the 2005-2006 storage season because wheat could not be obtained at the CGHAR until mid-September 2005. By that time, it was far past the time where the wheat could be stored for comparison to the previous year. Consequently, the wheat was aerated to reduce its temperature below 10°C using the cool autumn ambient air and held in storage at that temperature until the summer of 2006, when it was reheated to a normal summer harvest temperature (32°C). Each bin was loaded with about 27.2 t of wheat and had an airflow rate of 0.31 m^3/min/t ±5%. Bin loading, leveling, and insertion of temperature cables were completed on 24 July 2006. Sampling and recording of insect species was done as described before, on slightly different dates: 23 August, 20 September, 17 October, 20 November 2006, and 4 January 2007.

Data were analyzed separately for of the two storage seasons because of differences in weather patterns, which could also have affected the presence and abundance of particular insect species. Summaries were done for each year, and graphs of temperature patterns constructed using SigmaPlot software (SPSS, Chicago, Ill.). All data were summarized and analyzed by Chi-Square analysis using the Statistical Analysis System (SAS Insititute, 2008), in accordance with the analysis for a previous field study in other bins at the CGHAR (Arthur and Casada, 2005).

Results

2004-2005 Trial

In the 2004-2005 trial, the temperature at the north position was consistently lower in bins with suction versus pressure aeration (fig. 1) and was most apparent from the beginning of the test until about mid-October. The effect was more pronounced at the depth of 0.3 m, which would be

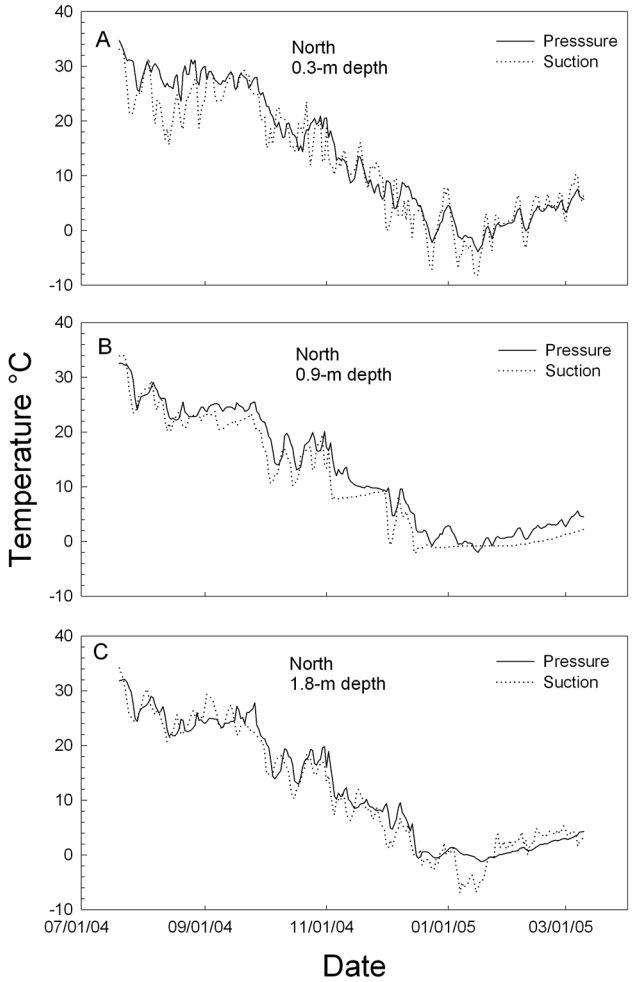

Figure 1. Average temperatures at depths of 0.3, 0.9, and 1.8 m at the north position during 2004-2005 in bins with pressure aeration vs. suction aeration.

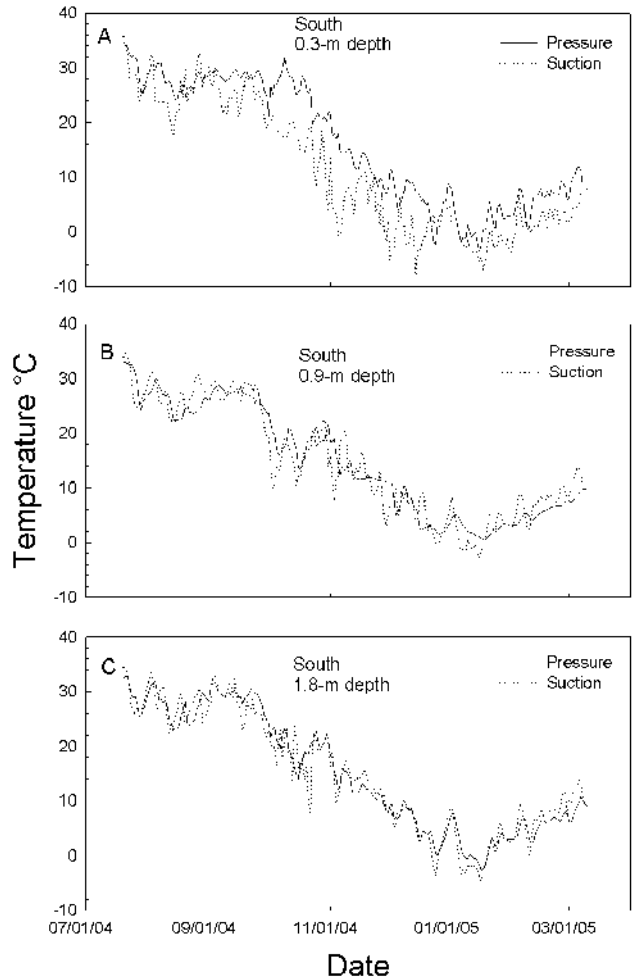

Figure 2. Average temperatures at depths of 0.3, 0.9, and 1.8 m at the south position during 2004-2005 in bins with pressure aeration vs. suction aeration.

considered the surface zone of the wheat mass (fig. 1A). At this depth, there was an immediate reduction in temperature compared to the other two depths of 0.9 and 1.8 m (figs. 1B and 1C, respectively), which showed lower temperatures but the patterns were not as pronounced as those at the upper surface zone. The lower temperatures nearer the surface were expected with the downward airflow suction systems and there was less of a difference between pressure and suction aeration with increasing depth, moving down toward the midpoint of the grain depth.

The patterns were repeated at the south position (fig. 2). Again, there was an immediate decrease at 0.3 m that was greater in bins with suction versus pressure aeration, especially at the depth of 0.3 m (fig. 2A). At 0.9 m, there appeared to be little overall difference in temperature between pressure aeration versus suction aeration until mid-October through the end of the calendar year, temperatures were consistently lower in bins with suction aeration versus pressure aeration (fig. 2B). At 1.8 m the effects of suction aeration were less evident deeper within the grain mass (fig. 2C), similar to the results for the north position at this depth.

The lower temperatures in bins with suction aeration were most apparent at the center position, which would be expected to be the position that was most stable and least influenced by outside air temperature or heating from solar radiation (fig. 3). At both the 0.3- and 0.9-m depths (figs. 3 A and B, respectively), there was an immediate drop in temperature in bins with suction aeration, and this pattern of cooler temperatures with suction aeration was consistent from the start of the experiment until the end of the calendar year, especially at the 0.9-m depth (fig 3B). As depth increased to 1.8 m, the temperature effects were less pronounced between the two aeration systems (fig. 3C).

If both treatments were aerated with identical mass flow rates and thermodynamic conditions of air, the temperature profiles resulting from aeration should be identical except for being inverted from top to bottom. There are several differences between mass flow rates and thermodynamic conditions of air for pressure and suction aeration that could cause small differences between profiles for the two treatments. However, the close agreement found between temperatures at the 1.8-m depth (near the mid-height of the grain mass) for both treatments indicates that any such differences were too small to be apparent in this study of the temperatures in the upper half of the bins.

For the trial conducted during 2004 to 2005, there were fewer *C. ferrigineus* and *T. castaneum* collected in traps from bins with suction aeration versus pressure aeration on all five sample dates (table 1). These seemed to be the most abundant

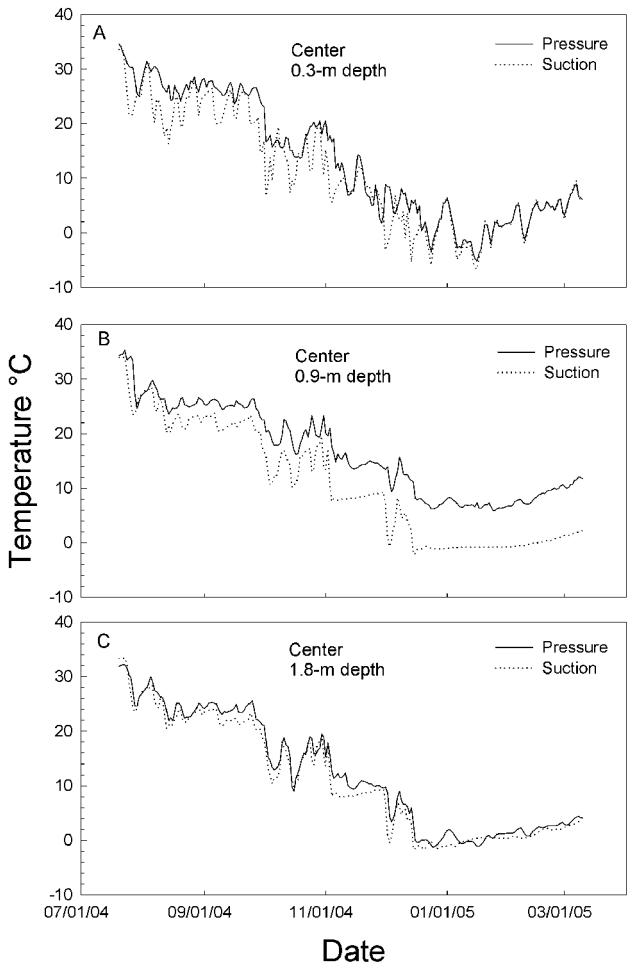

Figure 3. Average temperatures at depths of 0.3, 0.9, and 1.8 m at the center position during 2004-2005 in bins with pressure aeration vs. suction aeration.

insect pests, and for *C. ferrugineus* the totals trapped during the experiment were 3,290 and 662 in bins with suction versus pressure aeration, while for *T. castaneum*, there were 8,210 adults trapped in bins with suction aeration compared to only 722 in bins with pressure aeration. On all but one sample date there were less *A. advena* and *S. oryzae* in bins with suction versus pressure aeration. Data for *T. stercoria* were mixed, on one date there were more in bins with suction versus pressure aeration and on one date the order was reversed. Few *R. dominica* or *O. surinamensis* were found in any of the traps, with only one significant difference.

Insect population development is very dependent on temperature, therefore the data used to construct figures 1-3 were summed by creating a data set for each position and depth in both aeration systems that consisted of all dates from the start of the experiment through 31 December where temperature was >15°C, which is the threshold limit for population development of most stored-product insects. The resulting sums were compared through Chi-Square analysis. For all nine comparisons (three positions, three depths) the temperature summation was lower in bins with suction aeration compared to the bins with pressure aeration (table 2). This provides further confirmation of the reduced temperatures afforded by the suction aeration system.

2006-2007 Trial

During this trial, there was a noticeable reduction in temperature at the north position at depths of 0.3 and 0.9 m

Table 2. Sum of temperature units (daily average) above 15°C from 20 July through 31 December 2004 at depths of 0.3, 0.9, and 1.8 m at the north, south, and center positions in three bins with pressure aeration (P) and three bins with suction aeration (S).[a]

Depth (m)		North	South	Center
0.3	P	2593.1	2634.8	2331.1
	S	2039.6	2359.4	1811.1
0.9	P	2295.4	2506.5	2325.9
	S	1995.2	2168.1	1802.3
1.8	P	2293.9	2648.2	2161.4
	S	2033.5	2226.3	1817.7

[a] In all instances, the summation of temperature was lower in bins with suction (S) aeration vs. pressure (P) (Chi-square analysis, P < 0.01, SAS Institute).

Table 1. Sum of adults of each of seven species of stored-grain beetles trapped in three bins with pressure aeration (P) vs. suction aeration (S) during 2004.[a]

Species		29 July	27 Aug.	16 Sept.	14 Oct.	15 Nov.
Cryptolestes ferrugineus	P	89*	149*	1021*	506*	34*
rusty grain beetle	S	7	39	408	68	9
Ahasversus advena	P	442*	60	49*	55*	229*
foreign grain beetle	S	281	168#	1	1	0
Typhaea stercoria	P	338*	191	55	24	0
hairy fungus beetle	S	22	230	309#	34	0
Tribolium castaneum	P	46*	312*	6206*	1573*	73*
red flour beetle	S	2	41	667	10	2
Oryzaephilus surinamensis	P	0	14*	0	0	0
sawtoothed grain beetle	S	0	0	0	0	0
Sitophilus oryzae	P	12	359*	967*	692*	13*
rice weevil	S	8	51	183	118	0
Rhyzopertha dominica	P	1	0	7	13*	0
lesser grain borer	S	0	0	0	0	0

[a] Sums for P followed by an * indicates more adults for that species in bins with pressure aeration, sums for S followed by an # indicates more adults for that species were found in bins with suction aeration (P < 0.05, Chi-Square analysis, SAS Institute).

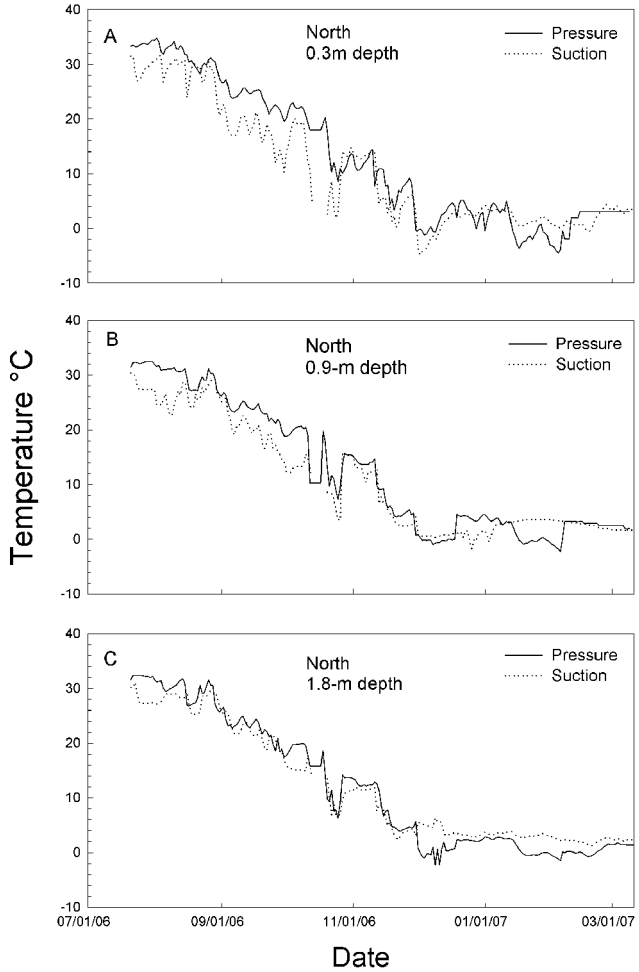

Figure 4. Average temperatures at depths of 0.3, 0.9, and 1.8 m at the north position during 2006-2007 in bins with pressure aeration vs. suction aeration.

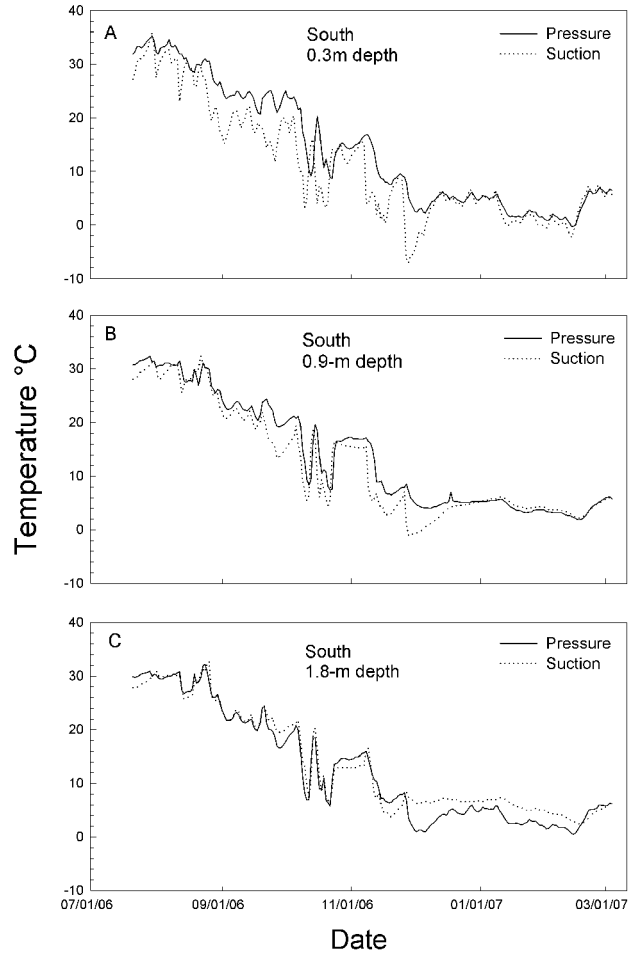

Figure 5. Average temperatures at depths of 0.3, 0.9, and 1.8 m at the south position during 2006-2007 in bins with pressure aeration vs. suction aeration.

(fig. 4A and B, respectively), from the initiation of the experiment through the first of November. Again, the effect was most evident at the upper position in the grain surface. However, even at the depth of 1.8 m, there was a rapid reduction in temperature in the bins with suction aeration versus pressure aeration (fig. 4C). At the south position, there was an immediate reduction in temperature with suction aeration (fig. 5A), but at 0.9 m, there was less of a temperature reduction until late September and early October (fig. 5B). The effects of suction aeration were again least evident at the south position at the depth of 1.8 m (fig. 5C), similar to the results for the 2004-2005 trial, although there was an overall lower temperature at this position in the bins with suction aeration as compared to bins with pressure aeration.

The reduction in temperature through suction aeration was again most evident in the center position at the depths of 0.3 and 0.9 m (fig. 6A and B, respectively), which would be less affected by ambient conditions compared to the north and south positions closer to the bin walls. Temperatures in the bins with suction aeration were consistently lower from the initiation of the trial until early November. At 1.8 m, there was a small immediate drop in temperature in bins with suction aeration at the start of the test and another in November (fig. 6C), but the overall patterns were similar to those in the north and south positions at this same depth.

Data for insect populations in the bins were slightly different in 2006-2007 regarding the insect species that were trapped in the bins and the abundance of those species (table 3). There were fewer *C. ferrugineus* trapped from bins with suction versus pressure aeration on all sample dates, which was similar to the data for 2004, even though the overall total trapped during the experiment was less than the total trapped in 2004. Still, in 2006 almost five times as many were trapped in bins with pressure versus suction aeration. Populations of *A. advena* were greater in suction versus pressure aeration on all three sample dates where significant differences occurred, in contrast to data for 2004. Inconsistent results were obtained for *T. stercorea*, as was the case in 2004. In 2006 there were more *T. castaneum* in bins with pressure versus suction aeration, but overall populations were lower than those in 2004. However, in contrast to the data obtained in 2004, there were few *S. oryzae*, but an abundant population of *O. surinamensis*, of which a total of 1637 were trapped during the experiment in bins with pressure aeration compared to a total of 30 from bins with suction aeration. As in 2004, few *R. dominica* were found in any of the bins. Thus, in 2006 there were virtually no internal infesters (*S. oryzae* or *R. dominica*) trapped in any bins,

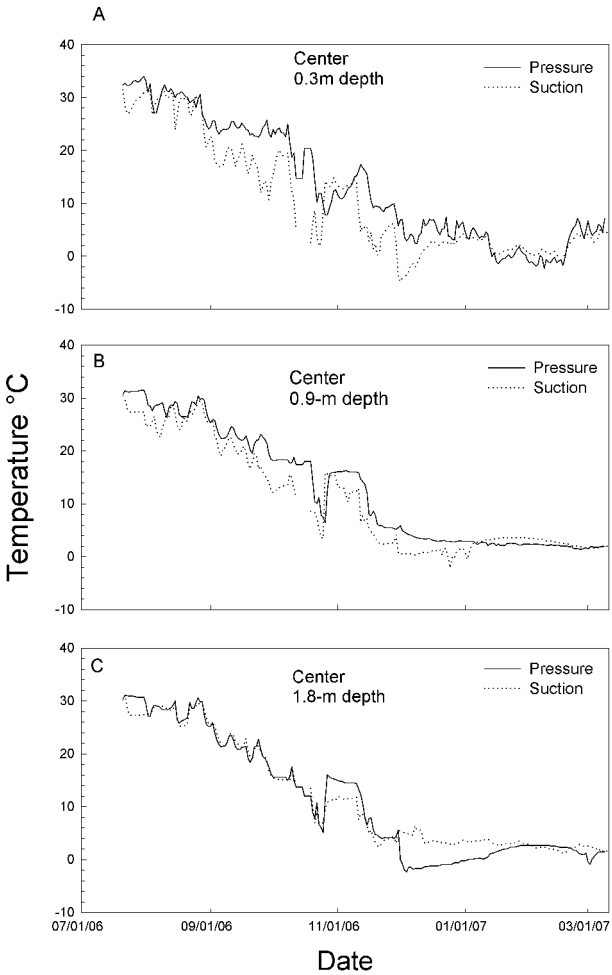

Figure 6. Average temperatures at depths of 0.3, 0.9, and 1.8 m at the center position during 2006-2007 in bins with pressure aeration vs. suction aeration.

unlike 2004 where the number of *S. oryzae* trapped reached almost 1000 in bins with pressure aeration (table 1). Although the species patterns and actual numbers varied between the two trials, in general there were fewer total insects trapped in bins with suction versus pressure aeration.

Data used to construct figures 4-6 were summed as for the first trial by creating a data set for each position and depth in both aeration systems that consisted of all dates from the start of the experiment through 31 December where temperature was >15°C. Again, for all nine comparisons (three positions, three depths, the temperature summation was lower in bins with suction aeration compared to the bins with pressure aeration (table 4). The actual numbers varied between tables 2 and 4 because of the different temperature patterns during the two time periods, but the comparison of treatments was the same, lower total temperature accumulation in the bins with suction versus pressure aeration. Table 4 also shows that the bin temperatures were lower in 2006 than in 2004, which is consistent with the lower numbers of insects trapped (tables 1 and 3) in 2006 as compared to 2004.

Table 3. Sum of adults of each of seven species of stored-grain beetles trapped in three bins with pressure aeration (P) vs. suction aeration (S) during 2006-07[a].

Species		23 Aug.	20 Sep.	17 Oct.	11 Nov.	4 Jan 07
Cryptolestes ferrugineus	P	1892*	1138*	227*	19*	14*
Rusty grain beetle	S	438	98	118	3	5
Ahasversus advena	P	122	13	8	0	0
Foreign grain beetle	S	265#	168#	94#	2	0
Typhaea stercoria	P	125*	30	0	0	0
Hairy fungus beetle	S	59	64#	14#	0	0
Tribolium castaneum	P	292*	128*	3	4	0
Red flour beetle	S	207	47	16#	9	0
Oryzaephilus surinamensis	P	418*	1190*	25	3	1
Sawtoothed grain beetle	S	19	4	6	0	1
Sitophilus oryzae	P	0	1	0	0	0
Rice weevil	S	1	1	0	0	0
Rhyzopertha dominica	P	2	2	6	0	1
Lesser grain borer	S	12#	5	3	0	0

[a] Sums for P followed by an * indicates more adults for that species in bins with pressure aeration, sums for S followed by an # indicates more adults for that species were found in bins with suction aeration ($P < 0.05$, Chi-Square analysis, SAS Institute).

Discussion

In a previous field study, we demonstrated that an initial summer aeration cycle led to lower insect populations in stored wheat compared to waiting for temperatures to cool in autumn and initiate the first cycle at the standard threshold of 15°C (Arthur and Casada, 2005). The results of this study showed that suction aeration was far more efficient for cooling the upper surface of the stored wheat mass compared to pressure aeration. Using suction aeration for the summer cooling cycle gave an immediate temperature reduction in the upper surface of the grain mass, which generally resulted in dramatically lower insect pest populations as measured by the numbers collected in the pitfall traps.

We used pitfall traps to estimate the insect pest populations, rather than using direct grain sampling, which can be labor-intensive and cumbersome. However, the actual insect numbers caught in pitfall traps are influenced by a number of factors, including grain temperature, the particular insect species, and the duration of the trapping interval (Fargo et al.,

Table 4. Sum of temperature units (daily average) above 15°C from 24 July through 31 December 2006 at depths of 0.3, 0.9, and 1.8 m at the north, south, and center positions in three bins with pressure aeration (P) and three bins with suction aeration (S).[a]

Depth (m)		North	South	Center
0.3	P	2323.3	2287.9	2208.3
	S	1836.1	1668.6	1649.7
0.9	P	2221.5	2155.3	2061.4
	S	1849.3	1720.9	1609.1
1.8	P	2177.2	2075.2	1990.6
	S	1977.5	1758.6	1709.1

[a] In all instances, the summation of temperature was lower in bins with suction (S) aeration vs. pressure (P) (Chi-square analysis, $P < 0.01$, SAS Institute).

1994; Hagstrum, 2000; Athanassiou et al., 2003; Stejskal et al., 2008). We tried to maintain consistency with the trapping intervals, but there was still considerable variation in insect species collected in the individual traps and the overall species composition, which is consistent with our previous study (Arthur and Casada, 2005). Insect distribution within a bin often does not follow a uniform pattern, but is instead patchy and random (Arbogast et al., 1998; Arbogast et al., 2000; Hagstrum, 2000, 2001; Nansen et al., 2004). This patchy distribution would account for the variation, and hence why we analyzed the data by Chi-square analysis rather than standard mean separation tests.

One factor that is apparent in our study is that seasonal and yearly differences in weather had an influence on the species composition in the bins. Since we did not artificially infest these bins, the populations emigrated from the immediate surrounding area of our research center, which includes a small-scale grain elevator with individual storage units. Optimal temperature for development of *S. oryzae* is generally in the range of 22°C to 27°C (Howe, 1965; Fields, 1992), and in controlled laboratory studies, results indicate greater reproduction in *S. oryzae* at 27°C versus 32°C (Arthur and Throne, 2003), however, the reverse was true for *R. dominica* (Vardeman et al., 2006; Chanbang et al., 2007). July of 2004 was relatively cool compared to most years, which could have accounted for the high populations of *S. oryzae*. The initial months of storage in 2006 followed a more normal pattern, and the result was low populations of *S. oryzae*, but increased populations of *O. surinamensis*. Nevertheless, even with the changing species compositions between the two storage periods, the overall results showed reduced grain temperatures in the upper portions of the wheat mass bins with suction versus pressure aeration. This difference was reflected in the insect populations in this upper surface zone, as estimated by the pitfall traps.

Although a number of previous field studies have demonstrated the effectiveness of aeration for controlling insect pest populations in wheat during the summer months in the central and southern plains of the United States (Reed and Harner, 1998a,b; Arthur and Casada, 2005), and in rice stored in Arkansas (Ranali et al., 2002) and in eastern Texas (Arthur et al., 2008), our study shows that the direction of the airflow may be an important factor that should be further investigated. Suction aeration could cool the upper surface of the grain mass more quickly than could be accomplished through standard pressure aeration, and since this surface zone is the initial focal point for most insect infestations (Vela-Coiffier et al., 1987; Hagstrum, 2001), a more efficient cooling of this zone would limit the scope and severity of the infestation. One benefit could be reduced reliance on the fumigant phosphine for control of insect pest populations. However, our tests were conducted with a comparatively small grain mass compared to large farm storages or commercial sites, further studies should be conducted on large bulk grain masses to more accurately assess the benefits of suction aeration during the initial months of grain storage.

Conclusion

Studies conducted in small-scale grain storage bins showed that suction aeration resulted in lower grain temperatures in the upper portion of the grain mass during the first few months of storage. These reduced temperatures in bins with suction versus pressure aeration also led to lower insect pest populations, as determined by sampling with pitfall traps. Results were consistent with earlier studies showing that an initial cooling cycle during the summer months in wheat stored in the central and southern plains of the USA, rather than waiting for the traditional cooling cycle in early autumn, could be an important component of integrated control programs for stored grains.

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