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VALIDATION OF A FINITE–ELEMENT STORED GRAIN ECOSYSTEM MODEL

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ABSTRACT. *An axisymmetric finite–element model was validated with respect to predicting the heat, mass, and momentum transfer that occurred in upright corrugated–steel storage bins due to conduction, diffusion, and natural convection using realistic boundary conditions. Hourly weather data that included hourly total solar radiation, wind speed, ambient temperature, and relative humidity were used to model the corn temperature and moisture content during storage with no aeration, and with ambient and chilled aeration. Periods of aeration were simulated assuming a uniform airflow rate through the grain mass. Sixteen bins with a capacity of 11.7 t each and instrumented with temperature cables were available to validate the model using two years of measured corn temperatures and moisture contents during summer storage. The average standard error between the experimental and predicted temperatures was 2.4° C (1.1° C to 5.7° C range), and the standard error between experimental and predicted moisture contents was 0.7 percentage points. The average standard error was 1.5° C in three non–aerated bins with sealed plenums when corn temperature was predicted as a function of the natural convection equation. The predicted natural convection effect was not applicable unless the plenum was assumed sealed.*

Keywords. *Modeling, Aeration, Heat transfer, Mass transfer, Storage.*

Two important physical parameters that affect grain deterioration during storage are moisture content and temperature. These can be controlled using ambient or chilled aeration. Additional methods available to manage stored grain are insect monitoring and sampling, grain temperature monitoring, automatic control of aeration fans, biological and non–chemical pest control, and improved facility design (Krischik et al., 1995).

An important tool to evaluate best management practices for storage in a particular structure under specific grain and environmental conditions is a comprehensive stored grain ecosystem model. This article is the second of two articles and describes the validation of the PHAST–FEM numerical model developed by Montross et al. (2002).

Insects and fungi are the primary causes of grain deterioration during storage, both of which develop as a function of temperature, moisture content, and time. Grain spoilage due to fungi is often initiated by insect feeding resulting in moisture and temperature conditions that are suitable for fungal growth (Sauer, 1992). Grain spoilage due to fungi and mycotoxin development is a significant concern whenever grains are harvested at higher moisture contents and need to be artificially dried (Young and Fulcher, 1984; Romer, 1984). Incomplete drying and improper storage management, especially with respect to aeration, can lead to moisture accumulation and condensation problems in many storage structures.

Storage models need to include aeration routines because aeration cooling has potential to maintain grain quality. In temperate climates, the rate of growth of an insect population can be slowed by aeration with cool ambient air (Cuperus et al., 1986). Additionally, if low temperatures are attained rapidly and are maintained long enough, insects can be killed. Chilling of barley infested with *S. granarius* to 3° C to 4° C prevented the development of a severe infestation with approximately 97% control (Burrell, 1967). Another reason for aeration cooling is that at lower temperatures, insect population growth is slowed; if cooling is applied quickly, it prevents insects from acclimatizing. Desmarchelier et al. (1979) examined the influence of chilling previously fumigated grain. Populations that were not cooled recovered to detection levels after just 10 weeks, while those subjected to a fast cooling did not achieve detection level until week 34. Fields (1990) demonstrated that if cooling occurred rapidly during the fall when insects had not been previously exposed to cool temperatures, all adult *Cryptolestes ferrugineus* (Stephens) were killed. Conversely, if cooling occurred mid–winter, there was a 60% survival rate.

Under certain climatic conditions, aeration cannot completely inhibit insect activity even in temperate climates because it cannot prevent the development of grain temperatures that are optimum for stored–grain insects (i.e., 21° C to 29° C). Such temperatures occur in summer–harvested wheat, oats, rice, and in carry–over shelled corn (including

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food–grade yellow and white corn, and popcorn). For such situations, grain chilling may be utilized to maintain suitable storage conditions without the use of chemical protectants (Maier, 1994). Commonly, grain is stored in bins that either do not allow cooling because of a lack of aeration systems, or allow cooling to within several degrees of the minimum ambient temperature using conventional aeration systems. In contrast, grain chilling is defined as the cooling of grain independent of the minimum ambient temperature by using a refrigerated air system. In a grain chilling system, ambient air is ducted over a bank of refrigeration coils to decrease the air temperature. Because dry grain will absorb moisture from wet air, the air is reheated a few degrees to match the relative humidity to the equilibrium relative humidity of the stored grain.

The main objective of this research was to evaluate the accuracy of the corn temperatures and moisture contents predicted by PHAST–FEM based on data collected during two years of summer storage trials using no aeration, automatic ambient aeration, and automatic chilled aeration in 11.7–t bins.

Experimental Methods

The model was validated with field data collected at the Purdue University Post–Harvest Education and Research Center (PHERC) pilot bin facility (sixteen 2.75 m diameter × 3.05 m eave height bins with a level filled capacity of 11.7 t each) located at the Agronomy Research Center, West Lafayette, Indiana. Only the summer storage temperature and moisture content data were used during validation because drying and conditioning of the corn were required until early spring. In addition, the conditions during summer storage were expected to be the most extreme, and the model was intended primarily for storage simulation. The storage treatments investigated were no aeration and automatic chilled and ambient aeration.

Each bin had five temperature cables (located in the center and 0.3 m from the wall on the north, west, east, and south) with thermistors (six located on the center cable, five each on the other cables) located every 0.6 m starting 0.1 m from the plenum floor. Each bin had an aeration fan that delivered 2.3 m^3 min^{-1} t^{-1} and was automatically controlled using an OPIsystem (Calgary, Alberta). Ambient temperature and relative humidity data were obtained from the OPIsystem and total solar radiation from a LI–COR (Lincoln, Neb.) silicon pyranometer. Wind speed measured by the Applied Meteorology Group in the Purdue Agronomy Department was used. Hourly data were required to run the model, and missing values were estimated when data were lost due to storms, power failures, etc.

On 30 October 1997, 9.8 t of Pioneer Hi–Bred 3245 (Des Moines, Iowa) food corn was loaded into each of eleven bins to a depth of approximately 1.9 m. The corn was natural–air dried until the summer storage period, which continued from 28 May to 22 September 1998. The corn was fumigated, unloaded, and the bins cleaned before 9.8 t of Pioneer 34K77 was loaded into each of fourteen bins on 21 October 1998. The corn was natural–air dried for the summer storage period, which continued from 1 May to 4 October 1999. Three temperature cables in the bins, south (S), center (C), and north (N), which each had three thermistors buried in the corn 0.1 (T1), 0.7 (T2), and 1.3 m (T3) from the plenum floor, were used to verify the predicted corn temperatures in each bin. The model was solved using an assumption of axisymmetric conditions. Therefore, the south portion of the bin was solved independently of the north portion of the bin. Due to the shading effect on the bins, the east and west cables were not used in the validation of the model. Table 1 lists the variables used for the validation of the PHAST–FEM model.

Aeration Schemes

The automatic ambient aeration scheme was based on a strategy similar to the SentryPAC (Sentry Technologies, Chico, Cal.) aeration storage mode 1. A large amount of runtime was desired because the bins were small and warmed up relatively quickly. The budgeted fan runtime per day was set at 4 h with an initial backlog of 24 h. This allowed for a greater amount of runtime during the storage season in order to attempt to recool the entire grain mass every couple of nights. The backlog was used to adjust the temperature and EMC bands around target values. The target moisture content was set at 14.5%, and the target temperature was the 21–day average ambient temperature. The target temperature was limited to a maximum value of 21.1°C. The maximum ambient air temperature that the fan was allowed to operate at was set to 26.7°C. The EMC band around the target moisture content was initially set at ±0.5% and expanded by multiplying the daily backlog (in hours) by 0.0375. The temperature band was initially set around the 21–day average temperature ±0.6°C and expanded by multiplying the daily backlog by 0.075. Additional details of the aeration scheme can be found in Montross (1999).

A grain chiller provided air at a flow rate of approximately 0.6 m^3 min^{-1} t^{-1} to three bins. However, airflow rates were intermittently measured using a hot–wire anemometer and varied between 0.3 and 1.1 m^3 min^{-1} t^{-1} because a chiller varies the airflow rate to hold a fixed temperature and relative humidity depending on the ambient conditions (Maier, 1992). The chiller was a prototype grain chiller developed

Table 1. Input parameters used for validating the model simulation predictions.

Parameter	Value
Slope of roof	40°
Height of wall in headspace	1.0 m
Height of plenum	0.3 m
Infiltration rate into plenum[a]	3.0 volumes/h
Infiltration rate into headspace[a]	3.0 volumes/h
Heat transfer coefficients:[b]	
inside wall and roof	4.0 W m^{-2} °C^{-1}
to grain surfaces	1.0 W m^{-2} °C^{-1}
Bulk density	612 kg/m^3
Specific heat[c]	1465 + 35.6*M (J kg^{-1} °C^{-1})
Thermal conductivity[c]	0.1409 + 0.00112*M (W m^{-1} °C^{-1})
Porosity[c]	0.38
Long–wave emissivity[d]	0.26
Short–wave emissivity[d]	0.66
Permeability[e]	3.5×10^{-9} m^2
Equilibrium moisture content	Modified Henderson equation[c]

[a] Maier (1992).
[b] Muir et al. (1980).
[c] Brooker et al. (1992).
[d] Kreith (1976).
[e] Khankari et al. (1995).

jointly by Purdue University and AAG Manufacturing, Milwaukee, Wisconsin (Maier and Rulon, 1996). Air was provided to each bin through an insulated duct that was manifolded into the three bins to keep the airflow approximately equal into each bin. The chiller was initially operated manually at night until 17 July 1998. After 17 July 1998 and during the entire 1999 summer storage period, the chiller was controlled automatically according to the thermistor located at a depth of 1.3 m above the plenum floor on the south cable of bin 15, which was the last bin to receive chilled air. Whenever the thermistor exceeded 12.8° C and the time was between 8 p.m. and 7 a.m., the chiller would run until the grain temperature decreased below 12.8° C or until 7 a.m., whichever came first.

Model Validation Results

Verification of Corn Temperatures

Figure 1 shows the predicted and measured temperatures at 0.7 m (C2) from the plenum floor on the center cable in a non–aerated bin during the summer of 1999. When the storage model was solved using the predicted natural convection currents that develop as a result of temperature gradients normal to the force of gravity, heat transfer was driven by conduction. However, the measured temperature increases and decreases that began around 26 May, 18 June, and 13 July were believed to be a result of increased convective heat transfer. The temperature increases and decreases look similar to an aeration front at a very low velocity. A number of effects not included in the natural convection equation could have increased the observed effect of convection currents, such as: (1) the shutters on the fans did not provide a perfect seal, and wind–induced air currents were generated through the grain mass; (2) the interstitial air within the grain mass was at a cooler temperature than the headspace air during the day, and as the cooler air settled down through the bin, the warmer headspace air replaced it (downdraft); (3) the headspace was relatively large compared to the grain mass, and during the day when the air in the headspace was heated due to solar radiation, it expanded and exited the headspace and was replaced by interstitial air from the grain mass (updraft); or (4) some combination of these effects.

Figure 2 shows the measured and predicted temperature in a bin with no aeration during the summer of 2001. During 2001, the fans in the no–aeration bins were physically removed and the plenum openings were sealed shut. The model predicted the grain temperature and moisture content (not shown) more accurately compared to a bin with an unsealed plenum (fig. 1). With a sealed plenum, heat transfer was driven by conduction. Changes in temperature occurred slowly and did not fluctuate much during storage. Based on this data, the natural convection equation (see eq. 7 in Montross et al., 2002) may not be applicable when the plenum is not fully sealed because wind–induced air currents and other phenomena may increase the heat transfer rate due to convection compared to conduction.

Given that none of the experimental bins for which data was collected in 1998 and 1999 had sealed plenums, a correction had to be made to more accurately model the observed phenomena in those bins. The predicted convection currents were ignored and a number of possible scenarios were simulated to increase the heat transfer due to convection: (1) a constant natural convection current (updraft or downdraft) through the bin as a function of wind speed, (2) a natural convection current that would reverse depending on the time of day, and (3) a natural convection current that would develop whenever a specified temperature difference existed between the grain and ambient air. By trial and error, it was determined that a constant–updraft natural convection current applied at every node independent of wind speed would yield the most acceptable results. Figure 3 demonstrates the effect of three continuous, upward natural

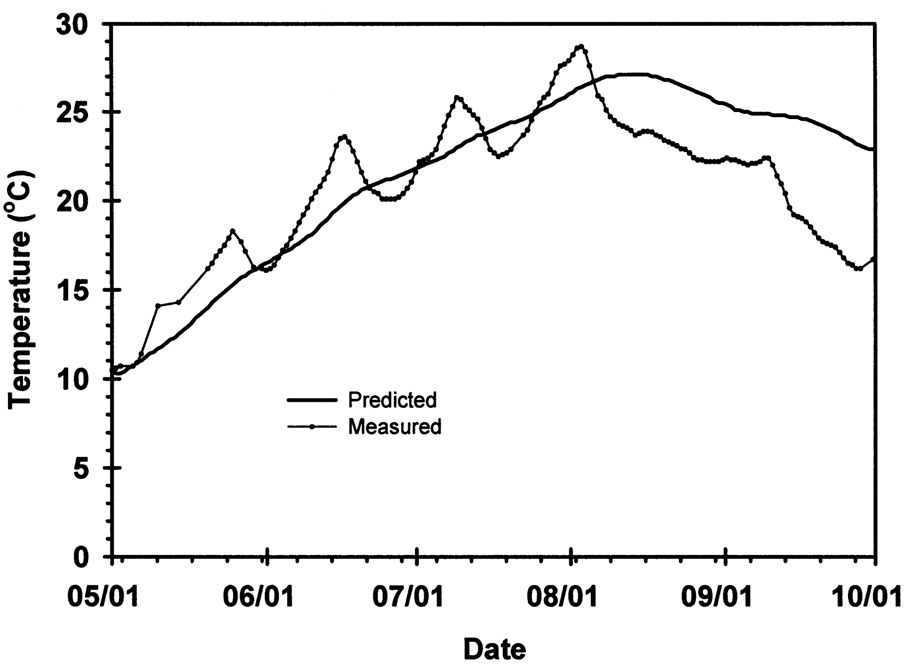

Figure 1. Measured and predicted temperatures 0.7 m from the plenum floor in the center of non–aerated bin 12 during the 1999 storage season when the model was solved using the predicted natural convection currents.

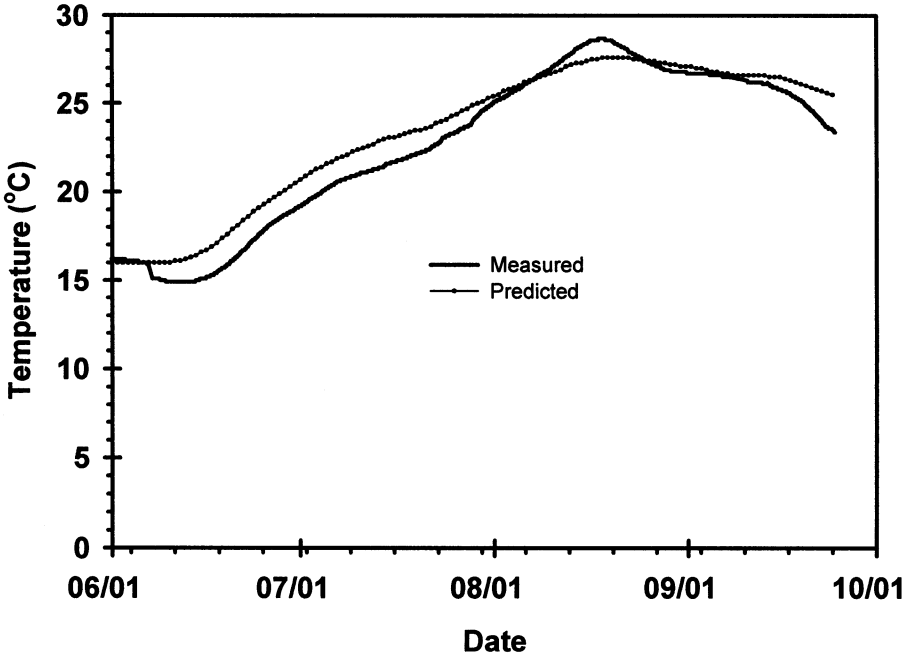

Figure 2. Measured and predicted temperatures 0.7 m from the plenum floor in the center of non–aerated bin 9 during the 2001 storage season when the model was solved using the predicted natural convection currents with a sealed plenum.

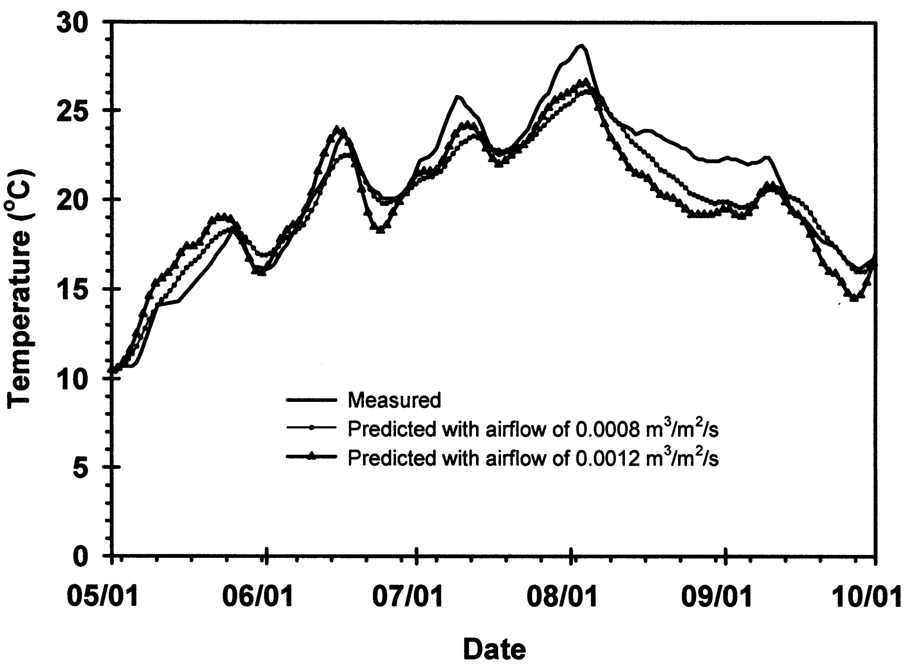

Figure 3. Measured and predicted temperature change as a function of two natural convection velocities 0.7 m from the plenum floor in the center of non–aerated bin 12 during the 1999 storage season.

convection currents on the predicted temperature change at C2 in non–aerated bin 12 during the 1999 storage season. By increasing the natural convection velocity the predicted temperatures matched the measured temperatures more closely.

However, the larger constant natural convection currents caused problems with the predicted moisture content. To reduce the predicted moisture loss, the smallest possible convection current was used that would yield acceptable accuracy in the temperature solution. It was determined that for all verification runs a constant upward convection velocity of 0.0008 m/s (69.1 m/d) through the grain mass at every node was acceptable. An air velocity of 0.0008 m/s corresponds to an airflow rate of 0.011 m^3 min^{-1} t^{-1}. A typical aeration fan would produce 10 times this airflow rate. However, this was a sufficient airflow rate to cause a substantial change in the temperature distribution of the grain mass. In comparison, the maximum predicted air velocity of the natural convection currents in a bin with a sealed plenum

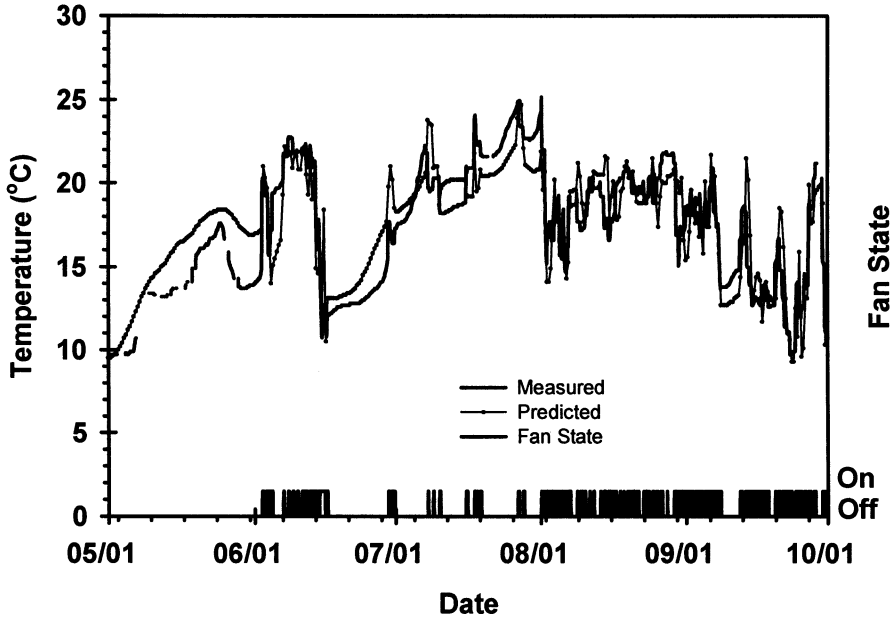

Figure 4. Measured and predicted temperatures 0.7 m from the plenum floor in the center and fan state in ambient–aerated bin 11 during the 1999 storage summer season using a constant natural convection velocity of 0.0008 m/s in the model prediction whenever the fan was not operating.

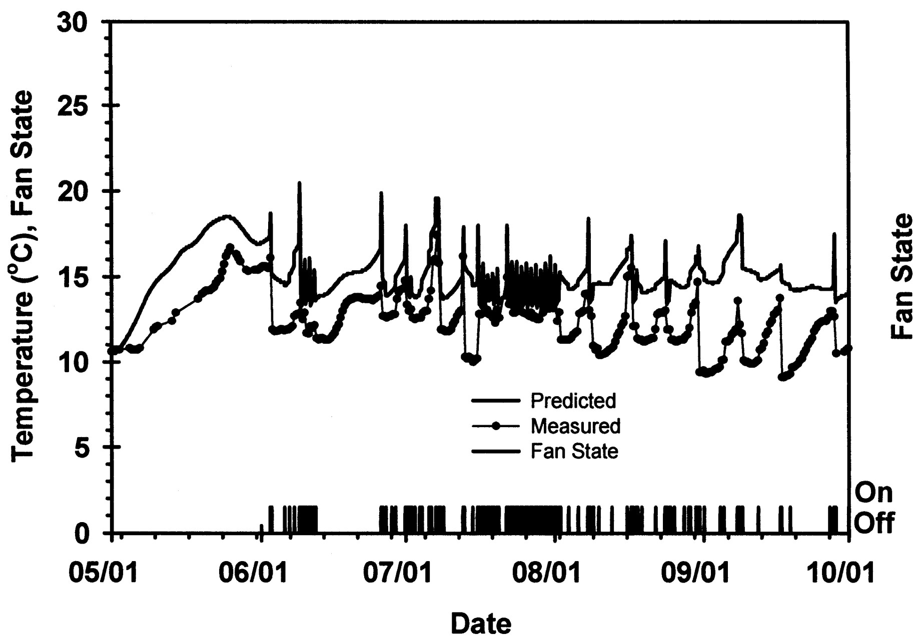

Figure 5. Measured and predicted temperatures 0.7 m from the plenum floor in the center and fan state in chilled bin 15 during the 1999 summer storage season using a constant natural convection velocity of 0.0008 m/s in the model prediction whenever the chiller was not operating.

was 1.3 m/d, 98% lower than the constant upward convection current that was applied to the bins with unsealed plenums.

Figure 4 shows the measured and predicted temperatures at C2 and the fan state in bin 11, which used automatic ambient aeration. The increase in temperature that occurred in the non–aerated bin around 18 June also occurred in the ambient aerated bin. The naturally occurring convection currents appeared to have been as strong in non–aerated as in ambient aerated bins.

The chilled bins were not as accurately modeled as the ambient and non–aerated bins. Figure 5 shows the temperature at C2 and the chiller state in bin 15. The predicted and measured temperatures in the chilled bins did not compare well because the data set required to model the prototype grain chiller was not available. Thus, the chiller was modeled as providing air at a constant temperature and relative humidity into the bin at a constant airflow rate of 0.6 m^3 min^{-1} t^{-1}, which was an approximate mean value based on intermittent measurement. Airflow rates out of the chiller were measured using a hot–wire anemometer and varied between 0.3 and 1.1 m^3 min^{-1} t^{-1}. If the required data were available, then a routine could be developed to model the throttled airflow from the chiller, which would increase the accuracy of the model predictions.

Table 2. Standard error[a] (° C) of the corn temperature at each sensor location and overall standard error during the 2001 summer storage season for the no–aeration storage treatment and sealed plenums.

Bin	Center Cable[b]			South Cable[c]			North Cable[d]			HS[e]
	C1	C2	C3	S1	S2	S3	N1	N2	N3	
3	1.1	2.1	1.8	1.0	2.1	2.1	1.5	2.6	2.0	5.6
5	1.1	1.0	1.0	0.8	1.1	1.0	1.1	1.6	1.4	6.5
9	1.1	1.1	1.0	2.5	1.5	1.6	1.6	2.6	2.3	6.5
Average	1.1	1.4	1.3	1.4	1.6	1.7	1.4	2.3	1.9	6.2

[a] Standard error = $\sqrt{\frac{(M_t - P_t)^2}{n}}$ where P_t = predicted temperature, M_t = measured temperature, and n = number of observations.
[b] C1 = thermistor 0.1 m from plenum floor, C2 = 0.7 m from plenum floor, C3 = 1.3 m from plenum floor.
[c] S1 = thermistor 0.1 m from plenum floor, S2 = 0.7 m from plenum floor, S3 = 1.3 m from plenum floor.
[d] N1 = thermistor 0.1 m from plenum floor, N2 = 0.7 m from plenum floor, N3 = 1.3 m from plenum floor.
[e] HS = headspace.

Table 3. Standard error[a] (° C) of the corn temperature at each sensor location, average standard error by treatment, and overall standard error for all treatments during the 1999 summer storage season.

Aeration Strategy[b]	Bin	Center Cable[a]			South Cable[a]			North Cable[a]			HS[a]
		C1	C2	C3	S1	S2	S3	N1	N2	N3	
NA	2	1.9	2.5	2.8	1.7	2.7	3.1	2.4	1.9	1.7	5.2
	4	2.7	2.0	2.1	4.6	2.2	1.7	1.7	1.9	2.3	3.7
	6	2.0	1.9	1.9	5.3	3.5	2.4	1.6	1.8	1.9	5.1
	8	2.8	2.3	2.4	3.8	3.0	2.5	1.8	2.1	2.5	5.1
	10	1.7	1.9	1.6	3.7	1.6	1.5	1.5	1.9	2.6	5.0
	12	2.0	1.3	1.2	2.6	1.7	1.6	1.2	1.9	2.2	4.5
Average NA		2.2	2.0	2.0	3.6	2.5	2.1	1.7	1.9	2.2	4.8
AA	3	1.7	2.5	2.2	3.8	5.0	3.6	1.8	2.4	2.2	5.7
	5	1.3	1.8	1.8	1.6	3.0	3.7	1.3	1.8	1.9	5.2
	7	2.3	2.7	2.5	4.4	3.5	3.7	2.0	2.1	2.2	5.0
	9	2.1	2.4	2.2	2.9	2.5	2.8	1.4	2.2	2.1	3.9
	11	1.2	1.9	1.8	2.4	3.2	3.0	4.3	2.1	2.4	4.8
Average AA		1.7	2.3	2.1	3.0	3.4	3.4	2.2	2.1	2.2	4.9
CA	13	3.4	2.8	2.6	2.4	1.3	1.8	1.9	2.3	2.8	4.4
	14	2.7	3.0	3.4	3.2	2.6	2.9	1.9	1.9	2.6	4.5
	15	2.4	2.3	2.6	5.7	2.8	2.3	4.0	3.9	2.8	10.6
Average CA		2.8	2.7	2.9	3.8	2.2	2.3	2.6	2.7	2.7	6.5
Overall average		2.2	2.2	2.2	3.4	2.8	2.6	2.1	2.2	2.3	5.2

[a] See table 2 for definitions of abbreviations.
[b] NA = non–aerated, AA = ambient aerated, and CA = chilled aeration.

The standard error of the predicted corn temperatures is shown in table 2 for non–aerated bins with sealed plenums during the 2001 summer storage period and for all bin treatments, table 3 for 1999, and table 4 for 1998. The predicted temperature along the centerline was approximately equal when the model was solved assuming a north– or south–facing wall (not shown). Overall, the average standard error was 1.5° C when the plenum was sealed and the predicted natural convection equation was used.

During 1999, the south cable had an average standard error of 2.9° C compared to 2.2° C for the center and north cables. The average standard error in 1999 by treatment was 2.2° C, 2.5° C, and 2.7° C for non–aerated, ambient aerated, and chilled aeration, respectively. During the 1998 storage season, the average standard errors were approximately 2.4° C, 2.2° C, and 2.3° C for the center, south, and north temperature cables, respectively. Bin 8 had a temperature distribution that was not consistent with the other bins and was eliminated from the calculation of average standard errors. During 1998 and 1999, the overall standard error was 2.4° C with a range of 1.1° C to 5.7° C for all aeration strategies. The same constant airflow rate of 0.0008 m/s was required to accurately predict the corn temperatures during the 1998 and 1999 storage seasons and for all aeration strategies.

Verification of Boundary Conditions

The predicted headspace temperature was consistently greater than the measured temperature during the day. This could have been due to the position of the sensor on the temperature cable that was chosen as being representative of the headspace temperature. (The fifth thermistor on the center cable was picked as being representative of the entire headspace because it was the closest thermistor to the center of the headspace). During periods of high solar radiation, a temperature gradient existed within the headspace air of the bin. The thermistor located 4 cm above the corn surface in the headspace was approximately 6° C cooler than the thermistor located 1.2 m above the grain surface in the headspace during periods of high solar radiation.

The standard error in the headspace temperature was 5.4° C in 1999 and 5.2° C during 1998. The error in estimating the headspace temperature was greater than the standard error at any thermistor within the grain mass.

Table 4. Standard error[a] (°C) of the corn temperature at each sensor location, average standard error by treatment, and overall standard error for all treatments during the 1998 summer storage season.

Aeration Strategy[b]	Bin	Center Cable[a] C1	C2	C3	South Cable[a] S1	S2	S3	North Cable[a] N1	N2	N3	HS[a]
NA	6	3.2	3.7	2.1	2.9	2.2	1.7	2.1	2.6	2.7	5.2
	12	1.2	1.6	1.6	1.5	1.1	1.1	1.6	2.3	2.3	6.0
Average NA		2.2	2.6	1.9	2.2	1.6	1.4	1.8	2.4	2.5	5.6
AA	5	1.3	2.2	2.3	1.3	2.0	2.1	1.5	1.9	2.0	5.7
	7	2.1	3.4	3.1	2.1	3.2	3.1	1.7	2.6	2.6	5.7
	8	1.6	3.0	3.0	8.7	5.6	4.0	2.2	3.0	2.6	5.5
	10	1.5	1.6	1.9	1.3	1.7	1.8	1.7	1.9	2.1	4.8
	11	1.5	2.2	3.9	1.6	2.3	2.3	2.3	2.7	2.7	4.9
	16	1.4	2.2	2.3	3.5	2.1	2.1	1.6	2.3	2.6	4.5
Average AA		1.6	2.4	2.7	3.1	2.9	2.6	1.8	2.4	2.4	5.2
CA	13	2.9	3.0	2.7	2.6	2.8	2.6	3.0	2.8	2.7	5.8
	14	2.6	2.9	2.5	2.6	2.8	2.7	2.5	2.8	2.7	5.9
	15	2.4	2.9	2.6	2.4	2.7	2.9	2.4	3.0	3.0	5.3
Average CA		2.6	2.9	2.6	2.6	2.8	2.7	2.6	2.9	2.8	5.7
Overall average		2.0	2.6	2.5	2.2	2.3	2.2	2.0	2.5	2.5	5.4

[a] See table 2 for definitions of abbreviations.
[b] See table 3 for definitions of abbreviations.

Table 5. Standard error of the roof and wall temperatures (°C), headspace relative humidity (percentage points), and the plenum and headspace grain surface temperatures (°C) of three bins during the 1999 summer storage season.

Bin[a]	S Roof[b]	N Roof[b]	S Wall[b]	N Wall[b]	Headspace RH[c]	Headspace Surface[b]	Plenum Surface[b]
AA 11	6.9	4.0	4.8	3.5	9.6	3.3	3.2
NA 12	6.2	3.8	4.7	3.6	11.7	2.8	3.4
CA 13	7.1	3.9	4.8	3.2	—	—	3.1

[a] AA 11 is ambient aerated bin 11, NA 12 is non–aerated bin 12, and CA 13 is chilled bin 13.
[b] S roof = thermocouple (TC) on south roof of bin, N roof = TC on north roof, S wall = TC on south wall, N wall = TC on north wall, headspace surface = TC on corn surface, plenum surface = TC on perforated metal plenum floor.
[c] Headspace RH = relative humidity of headspace air.

Table 6. Standard error of the roof and wall temperatures (°C) and headspace relative humidity (percentage points) of three bins during the 1998 summer storage season.

Bin[a]	S Roof[a]	N Roof[a]	S Wall[a]	N Wall[a]	Headspace RH[a]
AA 11	5.9	3.0	4.0	3.3	9.0
NA 12	6.1	2.5	3.7	3.2	—
CA 13	5.3	2.7	3.9	4.0	—

[a] See table 5 for definitions of abbreviations.

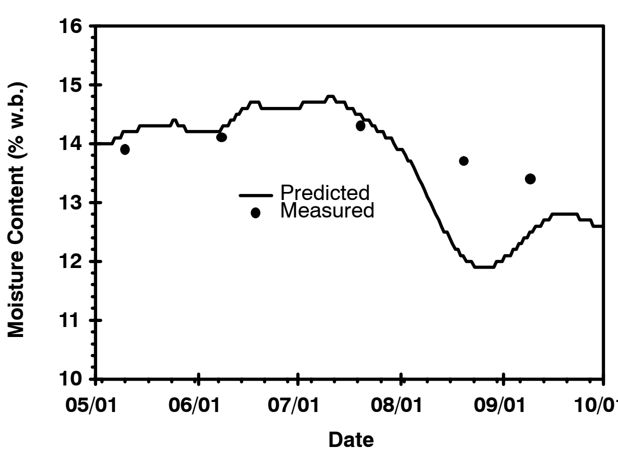

Figure 6. Measured and predicted moisture content change 0.7 m from the plenum floor in the center of non–aerated bin 12 during the 1999 storage season.

Three bins were equipped with additional thermocouples to measure the north and south roof and wall temperatures. In addition, thermocouples were placed in the center of two bins at the plenum–grain and headspace–grain interfaces during 1999. Those two bins were also equipped with relative humidity sensors. Table 5 presents the standard error for the three bins during 1999 and table 6 during 1998. The average standard errors for the calculation of the south roof, north roof, south wall, north wall, and headspace relative humidity over two years were 6.7°C, 3.9°C, 4.8°C, 3.4°C, and 10.8 percentage points, respectively.

Verification of Moisture Content

The moisture content was verified by manually probing the grain intermittently at three locations near the center of each bin. The moisture content of each sample was measured with a calibrated Motomco 919 moisture meter. Consequently, only limited points were available to compare the predicted versus the measured moisture contents. Figure 6 shows the predicted and measured moisture contents during the 1999 storage season in non–aerated bin 12. The predicted moisture content fluctuated due to the constant natural convection current assumed. However, the overall trend was similar to the measured values.

Table 7 shows the average standard error and the difference in the final average moisture content in each of the bins for the 1999 summer storage season and table 8 for 1998. The standard error of the moisture content was 0.4 points

Table 7. Standard error of the average moisture content (percentage points) and the overall error in the final average moisture content at the end of the 1999 summer storage season.

Aeration Strategy[a]	Bin	Standard Error	Error in Final MC
NA	2	0.6	–0.5
	4	0.4	–0.1
	6	0.4	–0.5
	8	0.3	–0.3
	10	0.3	–0.5
	12	0.6	–0.5
Average NA		0.3	–0.4
AA	3	0.2	–0.4
	5	0.3	–0.7
	7	0.5	–1.0
	9	0.5	–0.7
	11	0.4	–0.4
Average AA		0.4	–0.6
CA	13	0.2	–0.1
	14	0.5	–0.7
	15	0.4	0.0
Average CA		0.4	–0.3
Overall average		0.4	–0.5

[a] See table 3 for definitions of strategy abbreviations.

Table 8. Standard error of the average moisture content (percentage points) and the overall error in the final average moisture content at the end of the 1998 summer storage season.

Aeration Strategy[a]	Bin	Standard Error	Error in Final MC
NA	6	0.9	0.1
	12	0.7	0.1
Average NA		0.8	0.1
AA	5	1.3	–1.4
	7	1.5	–0.9
	8	1.4	–1.4
	10	0.7	–1.9
	11	1.5	–1.5
	16	1.4	–0.6
Average AA		1.3	–1.3
CA	13	0.6	–1.0
	14	0.5	–0.4
	15	0.6	–0.7
Average CA		0.6	–0.7
Overall average		1.0	–0.8

[a] See table 3 for definitions of strategy abbreviations.

during 1999 and 1.0 point during 1998. Overall, the model underpredicted the final average moisture content by 0.5 points in 1999 and by 0.8 points in 1998. Every aeration strategy except no aeration during 1998 underpredicted the final average moisture content.

DISCUSSION

A number of parameters are required to accurately predict grain temperatures during storage. The predicted natural convection currents did not yield realistic results in the pilot bins unless the plenum was sealed. It is believed that the pilot bins were more heavily influenced by wind than conventional–sized bins would be. However, natural convection currents induced by wind or some other phenomenon could also rewarm larger bins or amplify effects of moisture accumulation in the upper grain layers. In addition, the ratio of the headspace volume to corn quantity was considerably greater than in conventional bins. These factors reduced the effect of the natural convection equation in the pilot bins because the convective heat transfer was disproportionately larger than might be expected in conventional–sized bins. However, it is believed that the natural convection equation will be applicable to conventional–sized bins where wind–induced effects through the grain mass would be dampened. The observed effect of wind–induced drafts in poorly sealed bins could have major implications on storage management. The pilot bins were sealed with tape at the joints, and the roof was sealed at the wall sheets. During 2001, air could enter or exit the bin only through a single vent in the roof. Therefore, the natural convection currents originating from the plenum had a relatively small effect, which points to the importance of sealing aeration fans during storage.

The magnitude of the convection currents is strongly influenced by the permeability of the grain bulk, which has not been well documented for corn. Values of 1.61×10^{-8} to 5.96×10^{-9} m^2 (Sheldon et al., 1960), 2.52×10^{-8} m^2 (Hunter, 1983), and 3.5×10^{-9} m^2 (Khankari et al., 1995) for permeability have been used for shelled corn. A range of permeability values between 1.61×10^{-8} and 5.96×10^{-9} m^2 were investigated and a value of 3.5×10^{-9} m^2 seemed to produce the best results. At high permeabilities, the natural convection currents were too large and increased the convective heat and mass transfer rates to unreasonable levels. As the permeability was decreased, no natural convection currents developed and the heat transfer approached pure conduction. However, adjusting the permeability did not correct the underprediction of the heat transfer predicted by the natural convection equation.

The predicted headspace relative humidity was heavily influenced by the calculation of the headspace temperature, the infiltration rate of the ambient air, and the magnitude of the natural convection currents entering and exiting the grain surface. During model development it was assumed that the air in the headspace was turbulent and well mixed and therefore could be represented as a single temperature. Results from the pilot bins indicated that stratification occurred in the headspace air during periods of high solar radiation. However, in conventional bins with a proportionally smaller headspace it is expected that stratification would not be significant. To more accurately model the headspace relative humidity, a number of parameters would have to be obtained more precisely, such as the ambient air infiltration rate, mass transfer coefficients, and the heat transfer coefficients on the outside and inside of the bin. The largest error occurred in calculating the south roof temperature. A number of reasons exist for the large error in the calculation of the south roof temperature.

The heat transfer coefficient given by Finnigan and Longstaff (1982) was found to be too low when the roof temperature was significantly heated due to solar radiation and under conditions of low wind speed. By trial and error, the heat transfer coefficients on the outer roof and along the wall were increased by 50%, and a minimum wind velocity of 0.75 m/s was used when the heat transfer coefficients were calculated. This reduced the underprediction of the roof and wall temperature. However, as the heat transfer coefficients were further increased, larger errors occurred in the other predicted variables. In addition, the reradiation from the roof was estimated using a constant value of 30 W/m^2 (ASHRAE, 1985), which may not have been applicable for all roof temperatures and cloud cover levels. However, when reradiation was calculated, the solution became unstable. In addition, absortion of solar radiation had a major effect on the predicted temperature of the roof, wall, and average corn temperature. Values of 0.66 and 0.26 were used for the short–wave and long–wave emissivities, respectively, of new galvanized steel. Weathered galvanized steel has short–wave and long–wave emissivities of 0.89 and 0.28, respectively (Kreith, 1976). The average difference in the predicted overall corn temperature during non–aerated summer storage between new and weathered galvanized steel was 0.7° C (not shown). The radiation properties of the pilot bins were not known; however, the bins were two years old, and radiation properties of new galvanized steel were used.

The infiltration rate, roof and wall temperatures, heat transfer coefficients on the underside of the roof and inside of the wall, radiation properties, and the magnitude of the natural convection currents through the grain mass to predict the headspace temperature are not accurately known. These factors are the primary variables involved in estimating the headspace temperature and should be determined as part of a future research effort.

The equilibrium moisture content relationship of the corn hybrid stored in our pilot bins was not known. Some of the error in the predicted moisture content can be attributed to the choice of the equilibrium moisture content relationship and the constant natural convection currents applied. The modified Henderson EMC equation was used to predict the moisture content during storage. The modified Henderson equation consistently overpredicts the EMC compared to the Chung–Pfost equation (between 0.05 and 0.3 percentage points wet basis depending on the temperature and relative humidity). In addition, the constant natural convection currents had a tendency to decrease the average moisture content over the storage season. Lower natural convection currents decreased the error in the prediction of the moisture content.

SAS (1999) was used to determine if there was a significant difference between the standard errors between the two years of storage trials by aeration strategy, cable location, or thermistor location (significance level of 0.05). Overall, the standard error of the south cable was significantly higher than the north or center cables for both years and all aeration strategies. It was believed that errors in estimating radiation heat transfer and the convective heat transfer coefficients were the primary reasons for the higher standard errors on the south side of the bin.

Conclusions

The PHAST–FEM finite–element model developed to predict the heat and moisture transfer using realistic boundary conditions due to conduction, diffusion, and natural convection during aerated and non–aerated storage was validated. The following conclusions can be drawn:

- During 2001 when the plenum was sealed, PHAST–FEM accurately predicted corn temperatures using the natural convection equation. The average standard error was 1.5° C in three non–aerated bins.
- Natural convection currents as predicted by Darcy's law ranged up to 1.3 m/d. Natural convection values were not valid when the plenum was unsealed. Instead, accurate prediction of observed values required the assumption of a presumably wind–induced convection current of 0.0008 m/s (69.1 m/d).
- The average standard error for the nine thermistors in the grain mass, the two storage seasons, and the three aeration strategies was 2.4° C with a range of 1.1° C to 5.7° C. The average standard error in the moisture content was approximately 0.7 percentage points. The pilot bins at PHERC represent a worst–case scenario due to their small size and large temperature and moisture gradients compared to farm or commercial–sized bins. PHAST–FEM can be used to predict stored grain conditions in bins with a well–sealed plenum. The natural convection equation did not adequately predict air currents in bins without a sealed plenum.
- The available literature values for a number of critical variables proved to be too inaccurate. In order to further improve the prediction of the headspace and plenum air temperatures and relative humidities, and the roof and wall temperatures in corrugated steel bins, more accurate values for the following variables are required: convective heat transfer coefficients on the roof and wall due to the wind, convective heat and mass transfer coefficients inside the headspace and plenum, radiation properties of the bin construction material, and permeability of the bulk stored grain.

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