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Field Implementation and Model Validation of a Model-Based Fan and Burner Control Strategy for the In-Bin Drying and Conditioning of Corn

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FIELD IMPLEMENTATION AND MODEL VALIDATION OF A MODEL-BASED FAN AND BURNER CONTROL STRATEGY FOR THE IN-BIN DRYING AND CONDITIONING OF CORN

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ABSTRACT. *A new model-based self-adapting variable heat (SAVH) fan and burner control strategy for the in-bin drying and conditioning of corn was successfully implemented in three field experiments during the 2004 drying season. These experiments were carried out in three different locations throughout Indiana, in bins with different capacities (from 57 to 431 tonnes) and with two different corn types (yellow dent and white corn). One continuous natural air (CNA) experiment was also carried out drying yellow dent corn in a 57-tonne bin. The SAVH control strategy was able to successfully dry wet corn to a final moisture content (MC) close to 15%, with a relatively uniform final MC in the entire grain mass. Compared to the CNA strategy, the SAVH control strategy successfully avoided the overdrying of the grain under the same weather conditions.*

The Post-Harvest Aeration and Storage Simulation Tool - Finite Difference Method (PHAST-FDM) model was enhanced with the incorporation of three corn-type specific equilibrium moisture content (EMC) relationships, the adsorption and desorption EMC curves for the three corn types, and the differential airflow rate between the center versus side of the bin. The PHAST-FDM model was validated by comparing the observed MC values for the four experiments implemented during the 2004 drying season with the MC values predicted by the model. The model predicted MC distribution within the grain mass with a low error (standard error ranging from 0.44% to 0.70%).

Keywords. *Natural air/low temperature drying, Equilibrium drying model validation, Corn, Field test.*

A new model-based self-adapting variable heat (SAVH) fan and burner control strategy for the in-bin drying and conditioning of corn was developed. It incorporated the Thompson equilibrium drying model (Thompson, 1972) to predict moisture content (MC) changes in different layers of the grain mass. The SAVH strategy uses the Modified Chung-Pfost equation to predict the adsorption and desorption equilibrium relationships of the grain (*ASAE Standards*, 2001). The term "self-adapting" refers to the flexibility of the control strategy to better adapt to different weather conditions. The term "variable heat" refers to the ability of the control strategy to vary the amount of supplemental heat according to the weather conditions, when heat is needed. The drying model allows the SAVH control strategy to successfully identify wet versus dry weather conditions and respond to them appropriately. The SAVH control strategy was designed to minimize the overdrying of the grain during a low humidity drying season. Under those conditions, the SAVH control strategy selects the best fan operating hours and uses supplemental heat only when needed. During a high humidity drying season, the SAVH control strategy was designed to minimize drying time and drying cost by regulating the amount and frequency of supplemental heat (Bartosik, 2005).

Purdue University has a long history of successful application of simulation modeling to study in-bin drying and conditioning processes utilizing the Post-Harvest Aeration and Storage Simulation Tool – Finite Difference Method (PHAST-FDM) (Zink, 1998; Montross and Maier, 2000; Bartosik and Maier, 2004). PHAST-FDM was previously validated for several NA/LT in-bin drying experiments. However, the PHAST-FDM model had not been validated for the SAVH model-based fan and burner control strategy. Additionally, the incorporation of the SAVH strategy into the PHAST-FDM model required substantial improvements of the PHAST-FDM model.

The objectives of this research were: 1) to conduct a set of field experiments for the in-bin drying of different corn types utilizing the SAVH model-based fan and burner control strategy versus the continuous natural air (CNA) strategy; 2) to enhance the PHAST-FDM simulation tool to take into account adsorption and desorption equilibrium moisture content (EMC) relationships, three different corn types, and non-uniform airflow rates for the simulation of in-bin drying processes; and 3) to validate the PHAST-FDM simulation tool for the in-bin drying of different corn types with the CNA and SAVH strategies.

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Methodology

Description of the Experimental Setup for the Field Testing of the SAVH Control Strategy

The key components of the SAVH model-based fan and burner control system developed and utilized in this study were (fig. 1): (1) the weather station, which monitored the ambient temperature (T_a) and the ambient relative humidity (RH_a); (2) the plenum temperature sensor, which monitored the plenum drying air temperature (T_p); (3) the fan and burner control board (GSI Series 2000 in-bin drying system, The GSI Group, Assumption, Ill.) with a microprocessor custom-programmed to allow it to communicate via the serial port with the computer running the SAVH fan and burner control strategy; and (4) the computer and SAVH control strategy. The code to run the SAVH control strategy was written in LabVIEW 6.0 (National Instruments, Austin, Tex.).

The initial inputs required by the SAVH control strategy are grain type, grain depth, grain MC, airflow, and desired final MC. The goal of the control strategy is to always maintain the MC of the bottom grain layer between a lower and upper limit. The upper and lower MC limits are changed according to a proprietary strategy as drying progresses. Ambient temperature and relative humidity data are monitored during the entire drying season, and the ambient EMC is computed for the specific grain that is being dried. The MC of the bottom layer, the ambient EMC, and the lower and upper MC limits are the main criteria for turning on and off the fan and the burner. At the same time, the MC change of the bottom layer is updated based on the prediction of the Thompson equilibrium drying model, the airflow rate, the ambient temperature, and the ambient relative humidity data. More details about the SAVH strategy can be found in Bartosik (2005).

Description of the Experimental Sites for the SAVH Field Tests

During the 2004 drying season, three SAVH drying experiments (Experiments 1, 2, and 3) and one CNA drying experiment (Experiment 4) were carried out in West Lafayette (West-Central Indiana), Princeton (Southwestern Indiana), and Montmorenci (West-Central Indiana). The bins were constructed from corrugated-galvanized steel sections and equipped with a fully perforated drying floor, centrifugal fans, and a low pressure LP gas burner (The GSI Group, Assumption, Ill.). The bins were filled with wet yellow dent corn (Experiments 1, 2, and 4) and white corn (Experiment 3). The initial MC of the grain was obtained from samples periodically taken during bin loading. After the bins were loaded, the air velocity was measured on the surface of the grain at several locations at the center and side of the bin with an anemometer and a funnel (Bartosik, 2005). Several air velocity measurements at the center and side (close to the bin wall) were taken, and the average values for each location (center and side) were computed. The average measured air velocities at the center and side of the bin were converted into airflow rates ($m^3 min^{-1} tonne^{-1}$) as follows.

The diameter (D) of the upper end of the funnel is D_1 = 7.6 cm and the diameter of the lower end of the funnel is D_2 = 38.1 cm. Thus, the upper area (A) of the funnel is A_1 = 0.00456 m^2 and A_2 = 0.114009 m^2. The air velocity (V, m/s) was measured at A_1. Since the airflow (Q, m^3/min) is constant in the funnel, then $Q_1 = Q_2$. The air velocity at the grain surface (V_2) was then computed based on the following relationships:

$$Q_1 = A_1 \times V_1 \tag{1}$$

$$Q_2 = A_2 \times V_2 \tag{2}$$

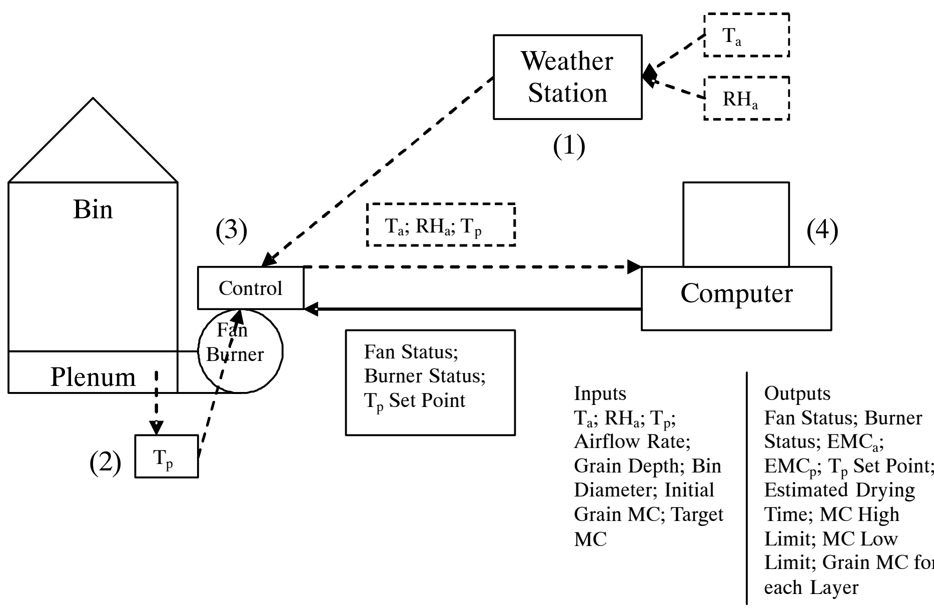

Figure 1. Diagram of the main components of the SAVH fan and burner control system and the flow of information among them. Dashed lines: input variables; solid lines: output variables; T: temperature, RH: relative humidity; EMC: equilibrium moisture content; MC: moisture content; Inputs: inputs required by the controller; Outputs: outputs provided by the controller. Subscripts a: ambient air; p: plenum air.

$$V_2 = \frac{Q_1}{A_2} \quad (3)$$

The average air velocity at the grain surface (V_2, m/s) was then multiplied by the bin area (A_b, m^2), and the total airflow was obtained (Q_t, m^3/s). This total airflow rate (Q_t) was divided by the total number of tonnes in the bin, and then multiplied by 60 s/min to obtain the final airflow rate (Q_f) in $m^3 min^{-1} tonne^{-1}$.

Garg (2005) studied the airflow distribution through the grain mass. He determined that the air velocity was not constant throughout a hypothetical grain column. At the core of the bin the air velocity was higher in the bottom layers than in the top layers. After approximately 1/3 of the grain depth from the bottom of the bin, the horizontal component of the air velocity increased significantly due to the higher fine material concentration. Part of the airflow was channeled from the core to the periphery of the grain mass, which caused the increase of the velocity profile at the periphery of the grain mass in the top layers. The airflow for the NA/LT in-bin drying experiments conducted for this research was estimated by measuring the air velocity at the grain surface. Thus, as a result of the findings of Garg (2005), the air velocity measured at the surface of the grain mass in the center and side of the bin presumably underestimated the air velocity (airflow) through the core of the grain mass and overestimated the air velocity through the periphery of the grain mass.

The SAVH model-based fan and burner control strategy does not take into account the vertical variability of the air velocity through the grain mass. The drying model incorporated into the SAVH control strategy as well as the PHAST-FDM simulation model use the assumption that each column of grain has a constant air velocity in all grain layers. This is a limitation of these models with the primary consequence of somewhat underestimating drying in the bottom layers of the core of the grain mass and overestimating drying in the bottom layers of the periphery of the grain mass.

During the experiments, bins were probed weekly with a vacuum probe (Port-A-Probe Model S, GVS Ltd., Prairie Village, Kan.) every 1 m (i.e., 0, 1, 2, 3 m, etc.) below the grain surface, and at two locations (in the center and near the sidewall). The grain MC was determined with a calibrated GAC-2100 analyzer (Dickey-John, Auburn, Ill.). The final target grain MC for all experiments was 15% (15% average final MC and 16% maximum). Table 1 summarizes the most important information for each one of these experiments.

PHAST-FDM In-Bin Drying Simulation Tool

The PHAST-FDM model was originally developed by Michl (1983) and is a numerical model that solves the heat and mass transfer during in-bin drying and conditioning in two dimensions (x,y). The model has undergone a series of significant modifications, most notably by Maier (1992), Adams (1994), Montross (1997), and Bartosik (2005) as part of this project.

Zink (1998) validated PHAST-FDM for popcorn in a commercial bin. Four conditioning and storage strategies were evaluated for Dodge City (Kansas) and Fort Wayne (Indiana) based on a selection of normal, good, and poor drying years. The harvest dates affected the drying strategy selection. He reported that the utilization of the entire historic weather database was preferred for the selection of site-specific conditioning and storage strategies.

Bartosik and Maier (2002, 2005) incorporated the variable heat (VH) strategy into the PHAST-FDM model. The PHAST-FDM model was then validated for in-bin drying of

Table 1. Information for the NA/LT in-bin drying experiments implemented at on-farm locations in Indiana during the 2004 drying seasons.

	Experiment			
Description	1	2	3	4
Location	W. Lafayette	Montmorenci	Princeton	W. Lafayette
Year	2004	2004	2004	2004
Drying system	SAVH	SAVH	SAVH	CNA
Grain	Corn (yellow dent)	Corn (yellow dent)	Corn (white)	Corn (yellow dent)
Target MC (%)	15	15	15	15
Bin diameter (m)	5.48	10.4	8.23	5.48
Fan (HP)	CF[a] 3 HP	CF 15 HP	CF 10 HP	CF 3 HP
LP gas burner (kW)	146.5[b]	146.5	146.5	–
Grain depth (m)	3.6	7.1	5.0	3.5
Airflow center (m^3/min/t)	1.53	0.62	0.93	1.64
Airflow side (m^3/min/t)	2.30	0.93	1.26	2.22
Tonnes	57.3	431.8	187.0	57.0
Initial drying date	19 Sept.	27 Sept.	14 Sept.	19 Sept.
Initial MC (%[c]	19.6	17.6	20.7	19.6
Initial MC St. Dev. (%)	1.24	N/A	1.24	1.09
Final drying date	28 Oct.	18 Nov.	26 Oct.	12 Oct.
Fan runtime (hours) [%]	879 [91.6]	855 [96.3]	881 [87.4]	553 [100]
Burner runtime (hours) [%]	253 [26.3]	412 [46.4]	462 [45.8]	N/A
Final MC (%)[c]	14.8	14.5	14.8	13.1
Final MC St. Dev. (%)	0.27	0.28	0.57	0.24

[a] Centrifugal fan.
[b] Equivalent to 500,000 BTU/h.
[c] Average values.

corn with the CNA and VH strategies. Bartosik and Maier (2004) used the PHAST-FDM model to evaluate the performance of the VH, continuous constant heat (CCH) and CNA strategies for four Midwestern locations, three airflow rates, and two harvest dates. They found that, based on the average drying cost of the 29 years analyzed, the VH strategy was the best choice for each location investigated. However, for most location and harvest date combinations, there were a number of years in which the lowest drying cost was observed for the CNA or CCH strategies. They also found that the ideal airflow rate for NA/LT in-bin drying was 1.1 $m^3 min^{-1} t^{-1}$, and that higher or lower airflow rates resulted in higher drying costs.

Enhancements of the PHAST-FDM Model

As part of this research, the PHAST-FDM model was enhanced in several ways to predict MC change during in-bin drying of grains more accurately.

The former PHAST-FDM version was written in FORTRAN. For this research the PHAST-FDM model was converted from FORTRAN into VISUAL BASIC. This provided the user with more possibilities of interaction with the application. The new VISUAL BASIC code has a set of default values and a simple menu where all of the basic parameter settings can be easily changed. In addition, the application has a set of windows with menus where all of the more advanced parameter settings are available for experienced users to change.

The former PHAST-FDM code consisted of a drying and a storage mode. The storage mode took into account the effect of solar radiation on the bin, which affected grain temperature mostly during long time periods when the fan was off. The new PHAST-FDM code kept the main features of the drying mode of the former code. However, it does not have a storage mode and thus does not take into account solar radiation because its effect is negligible for the drying process when fans are typically only off for a few hours at a time. The new PHAST-FDM code computes the dry matter loss (DML) of grain and takes into account the temperature increase due to DML respiration, a feature that was not available in the former version.

In addition to the fixed inlet air condition, CNA, EMC window, temperature window, relative humidity window, CCH, and VH strategies, the PHAST-FDM VISUAL BASIC code was expanded to incorporate the new model-based SAVH fan and burner control strategy.

The former PHAST-FDM model simulated drying using hourly temperature and RH data from the Solar and Meteorological Surface Observation Network (SAMSON) weather database, which included weather data from 1961 to 1990. The new PHAST-FDM application uses the National Climate Data Center (NCDC) Surface Airways (EarthInfo Inc., at www.earthinfo.com) hourly weather data, which includes 10 extra years of data (from 1961 to 2000).

In previous work, Bartosik and Maier (2006) reported a significantly higher concentration of BCFM in the core of the grain mass compared to near the bin wall. This higher concentration of fine material in the core of the grain mass reduced the airflow in this region, which caused a slower movement of the drying front. It was observed that the airflow rate measured at the center of the bin was about 30% lower than that measured close to the bin wall. Based on these observations, the new PHAST-FDM code was improved to handle non-uniform airflow by allowing the user to set different airflow rates through the center than through the side of the grain mass. The PHAST-FDM code independently solves the drying of grain for the center versus side of the bin. This feature of the PHAST-FDM in-bin drying simulation tool allows for a more realistic simulation of the drying process, and a more accurate prediction of the MC change in the bin.

The NA/LT in-bin drying process is highly affected by the ambient conditions during the drying period. As a result, the MC of the grain bottom layers is exposed to a series of drying and rewetting cycles. The EMC relationships for the drying and rewetting cycles are different. Thus, to better predict the MC change in the grain bottom layers, the PHAST-FDM in-bin drying simulation tool was equipped with a set of desorption and adsorption parameter values for the Modified Chung-Pfost equation (Bartosik, 2005).

Bartosik (2003) pointed out that there were significant differences among the parameters of the Modified Chung-Pfost EMC equation published in the different versions of the ASAE Standards (ASAE D245.4 and ASAE D245.5) (*ASAE Standards*, 2001). He also concluded that the use of variety-specific sets of EMC parameters would be a better alternative to the use of a single set of standard parameters to predict accurate EMC relationships for different types of grains. It was hypothesized that the use of different sets of parameter values might have a significant effect on the performance of the drying process. To address this problem, PHAST-FDM was equipped with a set of parameter values for the Modified Chung-Pfost equation for three different corn types, i.e., regular yellow dent, waxy, and white corn (Bartosik, 2005). The PHAST-FDM simulation tool also has the ASAE Standard D245.4 and D245.5 set of EMC parameter values for the Modified Chung-Pfost equation for yellow dent corn available. If new EMC parameter values for the Modified Chung-Pfost model (for any kind of grain) are developed in the future, these could be easily incorporated into the PHAST-FDM simulation tool.

Statistical Parameters Used to Evaluate the Prediction of the PHAST-FDM Model

Two main statistics were used to evaluate the accuracy of the prediction of the PHAST-FDM in-bin drying simulation tool: standard error of the residuals (SE), and the average of the absolute value of the residuals (AAVR).

$$S.E. = \sqrt{\frac{\Sigma(Y - Y')^2}{df}} \tag{4}$$

where Y is the measured value, Y' is the value predicted by the model, and df is the degrees of freedom of the model.

$$AAVR = \frac{\sum |Y - Y'|}{obs.} \tag{5}$$

where Y and Y' are defined as in equation 4, and obs. is defined as the number of observations.

Results and Discussion

Field Implementation of the SAVH Control Strategy

Comparison between the SAVH and the CNA Strategies

During the 2004 drying season, the SAVH and CNA strategies (Experiments 1 and 4, respectively) were implemented for drying yellow dent corn at West Lafayette, West-Central Indiana. Both bins were filled with approximately 57 tonnes of corn at 19.6% average MC. The bins were not equipped with grain spreaders, so the two bins were cored after being filled with corn. Approximately 6 tonnes of grain were unloaded into a wagon, and then filled back into the bin. The grain surface was leveled manually and the air velocity at the center and side of the bin was measured for each bin (table 1). Then, the airflow rate ($m^3 min^{-1} tonne^{-1}$) was calculated for the center and side of the bin as previously explained. Unfortunately, the coring operation did not improve the airflow distribution. The main reason was presumably that the amount of grain unloaded was not sufficient to eliminate a substantial enough amount of fines from the core of the grain mass. An additional contributing factor could have been that re-loading of the cored material, with a high fines concentration, on top of the grain mass reduced the initial positive effect of coring on the airflow distribution.

The SAVH Control System

A failure in the burner of Experiment 1 (SAVH) forced the implementation of the CNA strategy during the first week of drying (20 to 27 September). On 28 September the burner was replaced and, prior to the start of drying corn with the SAVH control strategy, the bin was probed for MC in different layers. The following information was required to initiate the SAVH control system: MC in different layers at the center and side of the bin (four layers, 1-m depth each), airflow rate at the center and side of the bin ($m^3 min^{-1} tonne^{-1}$), desired final MC (i.e., 15%), and grain type (yellow dent corn). The SAVH control strategy finished drying corn on 28 October. Experiment 4 (CNA strategy) was started on 19 September and the fan ran continuously until 12 October, when drying was completed.

The differential airflow rate at the center and side of the bin (table 1) caused the drying front to move faster at the side than at the center. For Experiment 1 (SAVH at West Lafayette) the measured airflow at the side was 2.30 $m^3 min^{-1} tonne^{-1}$, while it was 33% lower (1.53 $m^3 min^{-1} tonne^{-1}$) at the center. As a result, by 28 September the observed MC at the center were 13.9% and 16.6% for layers 1 and 2, respectively, while for the side of the same bin the observed MC for layers 1 and 2 were 13.8% and 14.6%, respectively (figs. 2 and 3) [Note: Layers 1 and 2 are the first and second layers from the bottom of the bin]. Figures 4 and 5 show the same effect due to the differential airflow rate for the CNA strategy bin (Experiment 4).

Figures 2 and 3 depict the change in the observed and predicted MC of corn while dried with the SAVH strategy. The goal of the SAVH control strategy was to maintain the MC of the bottom layer (Layer 1) between a lower and an upper limit. The SAVH control strategy has the ability of changing the MC limits according to a proprietary strategy as drying progresses (Bartosik, 2005).

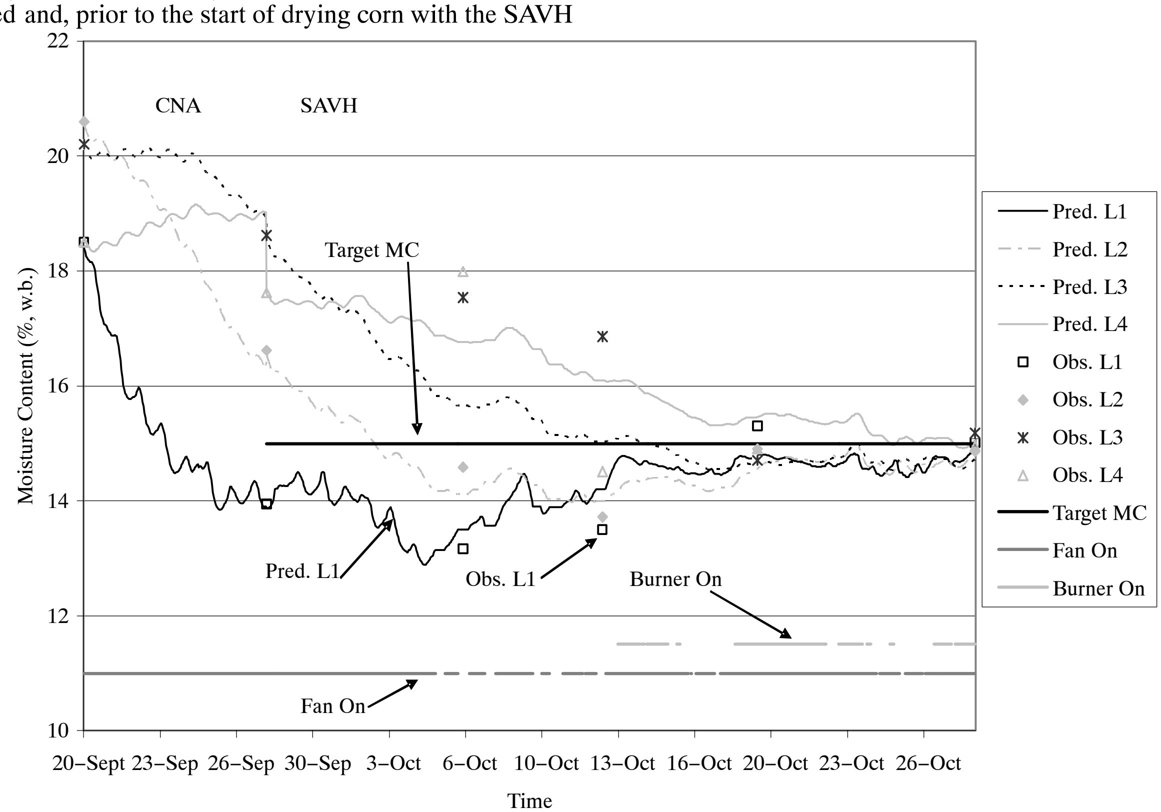

Figure 2. Predicted (Pred.) and observed (Obs.) moisture content changes in different layers at the center of the bin during the SAVH in-bin drying Experiment 1, target MC for the SAVH control strategy operation (Target MC) and fan and burner operating periods (Fan On and Burner On, respectively). Pred. L1 to 4: predicted moisture content values; Obs. L1 to 4: observed moisture content values, L1 = bottom, L4 = top. [Note: The gray area in the chart (from 20 to 27 Sept.) indicates that during the first week of drying the SAVH strategy could not be implemented, and the continuous natural air (CNA) strategy was implemented instead. After 27 Sept. drying continued with the SAVH strategy.]

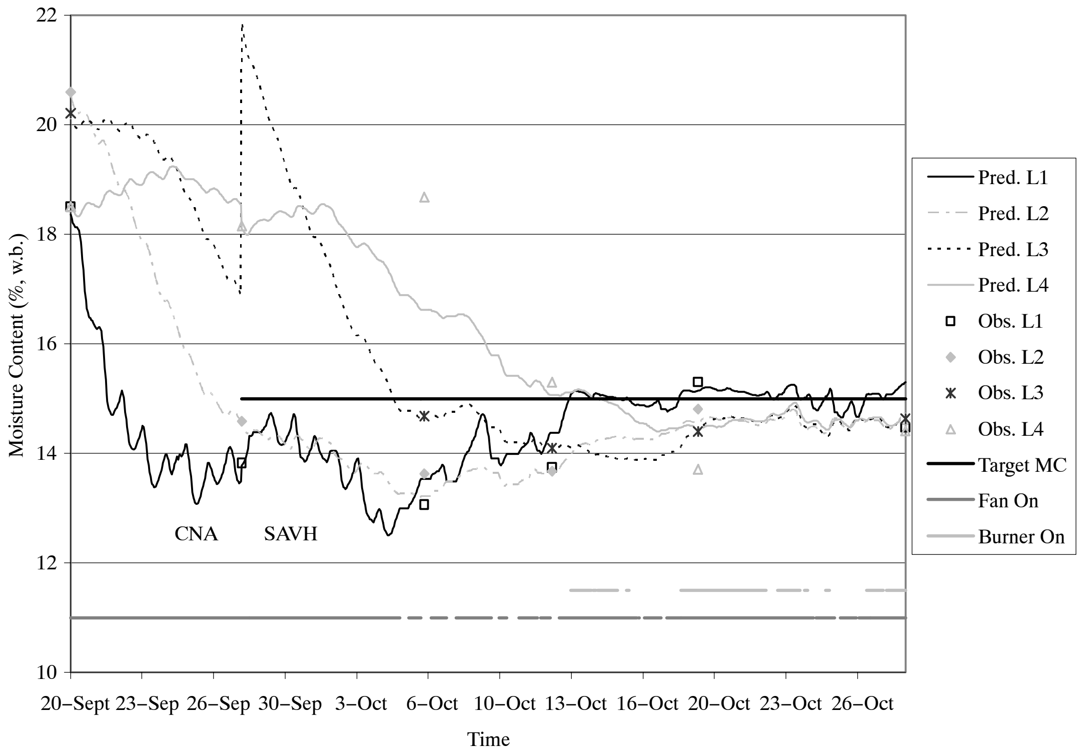

Figure 3. Predicted (Pred.) and observed (Obs.) moisture content changes in different layers at the side of the bin during the SAVH in-bin drying Experiment 1, target MC for the SAVH control strategy operation (Target MC) and fan and burner operating periods (Fan On and Burner On, respectively). Pred. L1 to 4: predicted moisture content values; Obs. L1 to 4: observed moisture content values, L1 = bottom, L4 = top. [Note: The MC of the grain sample for layer 3 at the side of the bin on 27 Sept. was substantially higher than the initial grain MC sample for the same layer. It is not clear why such a large increase in grain MC was observed, and was most likely caused by sampling error.]

When the SAVH control strategy was initiated on 28 September, the target MC was 15% and the predicted MC of the bottom layer were 13.8% and 13.9% for the center and side of the bin, respectively. As a result, the SAVH control strategy ran the fan continuously (fan “on”) without supplemental heat (burner “off”). As drying progressed, the SAVH control strategy started to adjust the MC limits from 4 to 12 October according to a proprietary strategy. During the last portion of the drying period (after 12 October), the SAVH control strategy selected the operating hours for the fan in order to bring the MC of the bottom close to the target MC of 15%. Figure 2 shows that the observed MC of the bottom layer (L1) increased from 13.2% on 6 October to 13.5%, 15.3%, and 15.0% on 12, 19, and 28 October, respectively. Figure 3 shows a similar trend in the observed MC change for the side of the SAVH experimental bin, where the observed MC of the bottom layer increased from 13.1% on October 6 to 14.5% on October 28. From 6 until 28 October the SAVH control strategy was able to reduce the overdrying of the grain bottom layer from 1.9% points to almost zero, while drying continued in the wet upper layers. The observed MC of the upper layer (L4) decreased from 18% on 6 October to 14.9% on 28 October for the center of the bin, and from 18.7 to 14.4% for the side of the bin during the same time period. After 13 October the weather turned wet during some periods (fig. 4), and the predicted MC of the bottom layer increased above the target MC. Immediately, the SAVH control strategy used supplemental heat (figs. 2 and 3, Burner “on” line) to bring the MC of the bottom layer below 15%. Figures 2 and 3 show that the observed MC of the bottom layer (L1, 19 October) also tended to increase above 15%, which confirmed the prediction of the drying model. For Experiment 1, the SAVH control strategy finished drying corn from 19.6% initial average MC to 14.8% final average MC (0.27% point standard deviation) in 38 days (removing 4.8% points of moisture). During this time period the fan was “on” 879 h (91% of the time), and the burner was “on” 253 h (26% of the time).

The CNA Strategy

Experiment 4 started on 19 September and dried corn with the CNA strategy. By 28 September the observed MC in the bottom layer (L1) overdried to 13.9% and 13.8% for the center and side of the bin, respectively. During the following two weeks, until 12 October, the ambient EMC was relatively dry (fig. 4). This produced significant overdrying, not only in the grain bottom layer, but in the entire grain mass (figs. 5 and 6). On 12 October the CNA experiment (Experiment 4) was completed. The observed MC of the bottom layer were 13.1% and 13.2% for the center and side of the bin, respectively, while the observed MC of the top layer (L4) were 13.5% and 13.3%, respectively. The CNA strategy finished drying corn from 19.6% initial average MC to 13.1% final average MC (0.24% points standard deviation) by 12 October (removing 6.5% points of moisture). For Experiment 4 the fan was ”on” during 553 h (326 h less than for Experiment 1), but due to the dry weather conditions of the early fall, the entire grain mass was significantly overdried (1.9% points average for the entire grain mass). By the same date (12 October), the experiment with the SAVH strategy (Experiment 1) had also overdried the bottom corn layer (13.7 and 13.5% MC for the

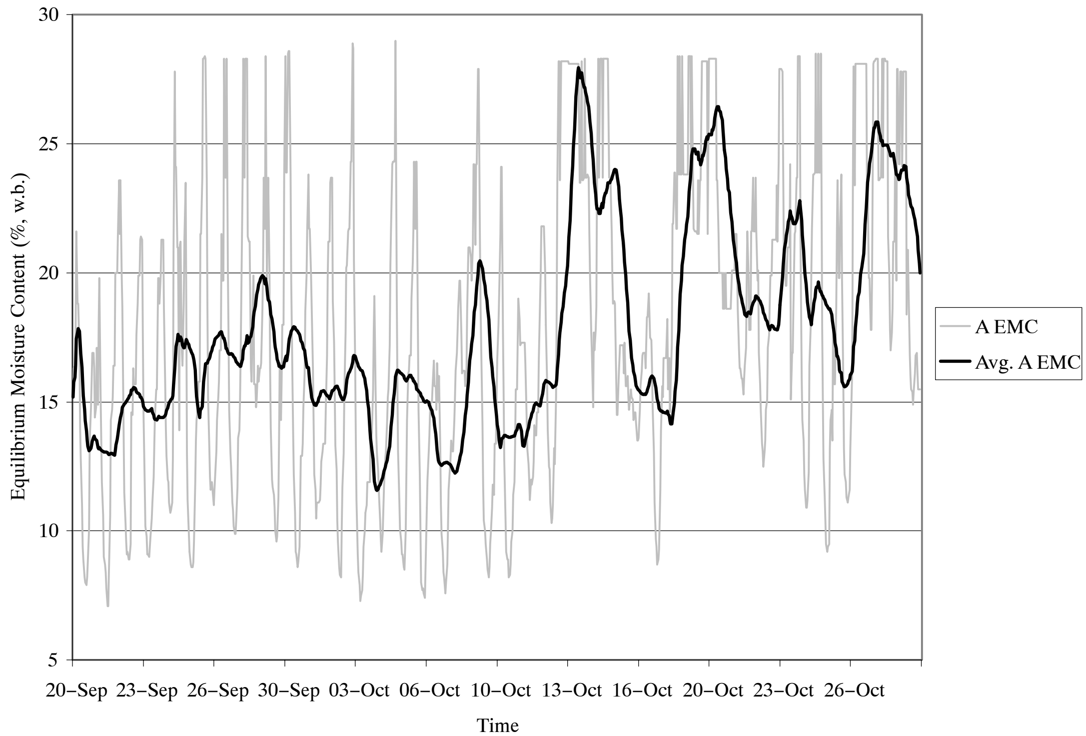

Figure 4. Equilibrium moisture content of the ambient air (A EMC) for yellow dent corn and 24-h rolling average of the equilibrium moisture content of the ambient air (Avg. A EMC) from 20 September to 28 October of 2004 for West Lafayette weather conditions. EMC determined based on the Modified Chung-Pfost equation and the yellow dent corn type parameters.

center and side of the bin, respectively) (figs. 2 and 3). However, after 5 October the SAVH strategy selected the appropriated fan run hours to continue drying corn in the upper layers while MC increased in the bottom layers (note the intermittent fan operation after 5 October in figs. 2 and 3). This important feature of the SAVH strategy gradually reduced the overdrying of the bottom layers by the end of the experiment.

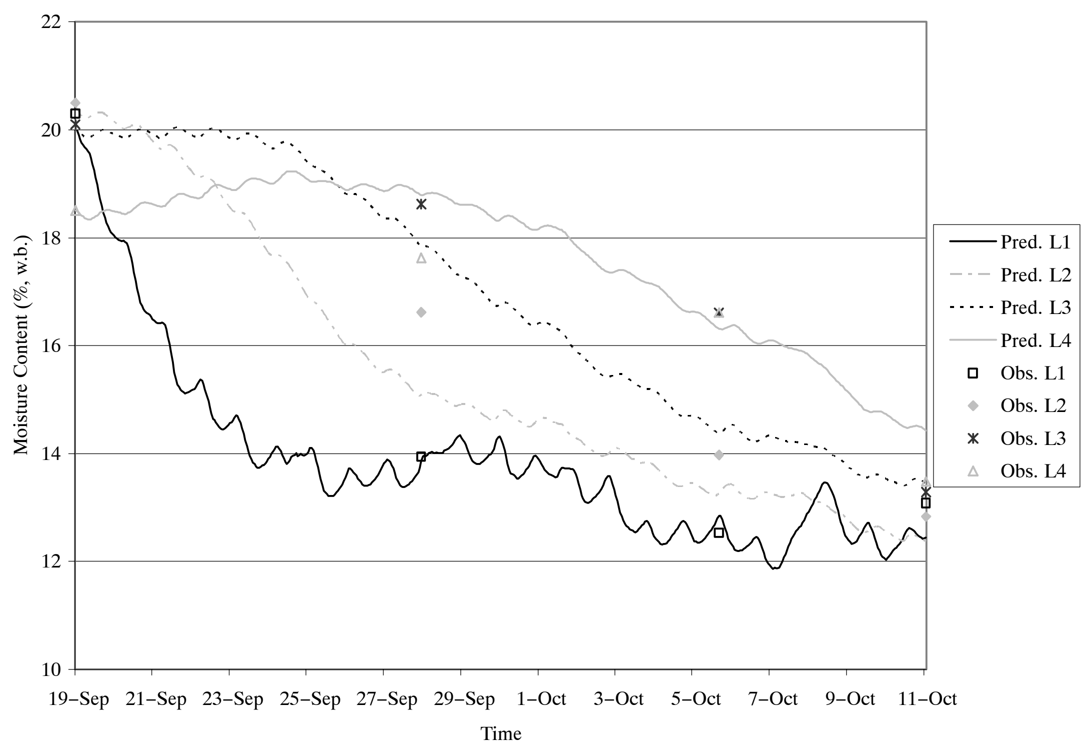

Figure 5. Predicted (Pred.) and observed (Obs.) moisture content changes in different layers at the center of the bin during the CNA in-bin drying Experiment 4. Pred. L1 to 4: predicted moisture content values; Obs. L1 to 4: observed moisture content values, L1 = bottom, L4 = top.

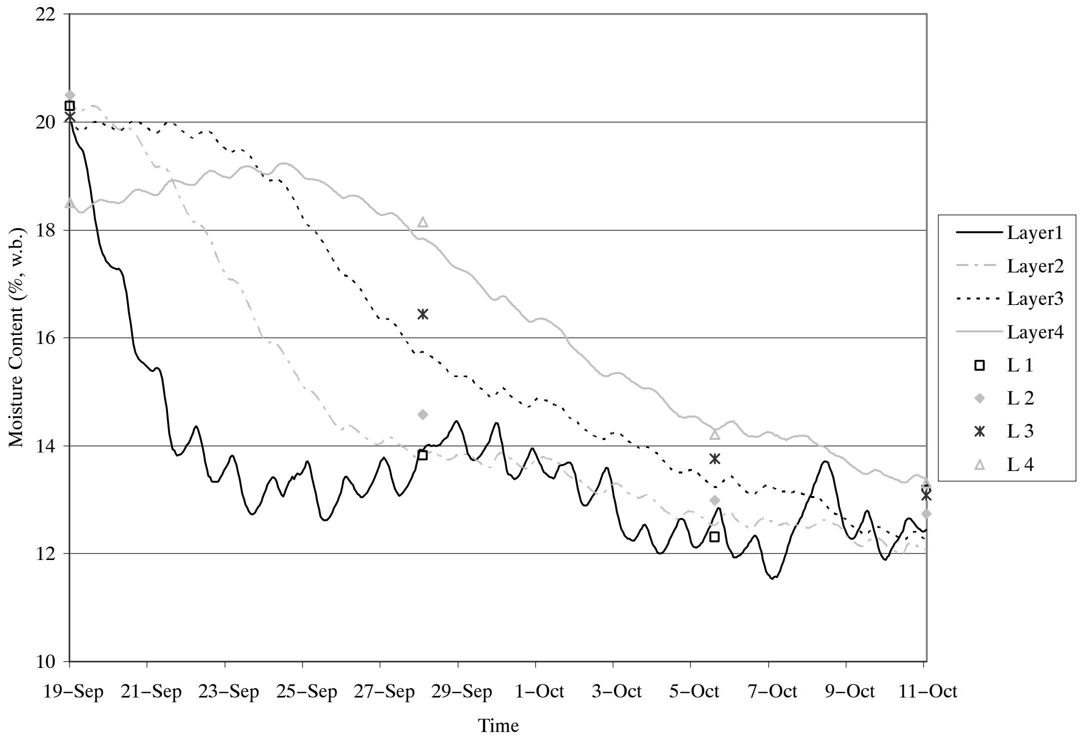

Figure 6. Predicted (Pred.) and observed (Obs.) moisture content changes in different layers at the side of the bin during the CNA in-bin drying Experiment 4. Pred. L1 to 4: predicted moisture content values; Obs. L1 to 4: observed moisture content values, L1 = bottom, L4 = top.

Other In-Bin Drying Experiments with the SAVH Control Strategy

Experiment 2 was carried out in Montmorenci, West-Central Indiana, drying yellow dent corn from 17.6% initial MC to 14.5% final MC (0.28% point standard deviation of the final MC). In this experiment, 432 tonnes of corn were binned on 27 September in a 10.4-m diameter and 7.1-m tall bin. After binning, the grain surface was leveled and the airflow rate was measured for the center and side of the bin. The low airflow rate (0.62 and 0.93 $m^3 min^{-1} tonnes^{-1}$ for the center and side, respectively) caused the drying front to move relatively slowly (figs. 7 and 8). In this experiment, 3.1% points

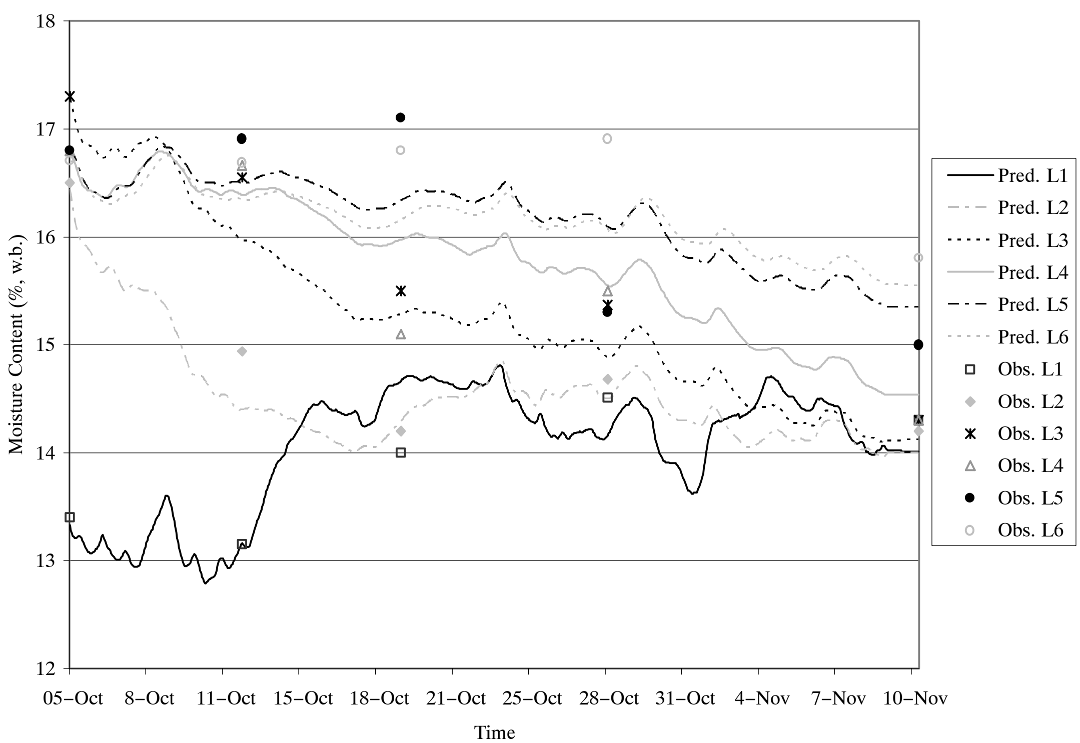

Figure 7. Predicted (Pred.) and observed (Obs.) moisture content changes in different layers at the center of the bin during the SAVH in-bin drying Experiment 2. Pred. L1 to 6: predicted moisture content values; Obs. L1 to 6: observed moisture content values, L1 = bottom, L6 = top.

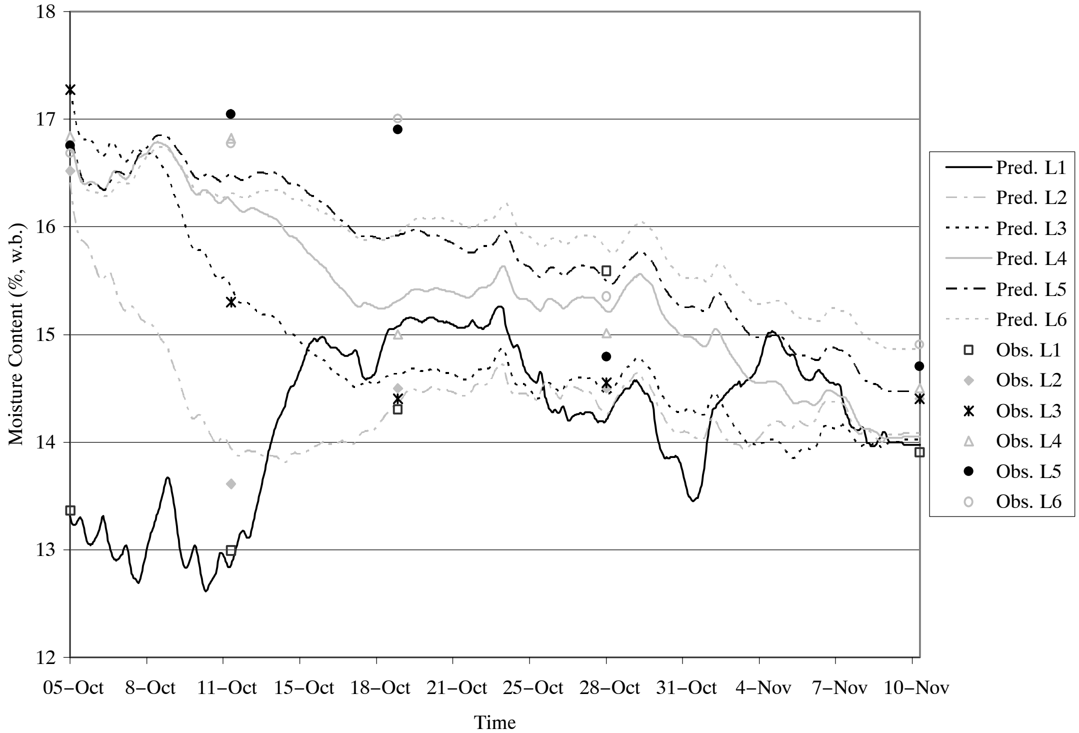

Figure 8. Predicted (Pred.) and observed (Obs.) moisture content changes in different layers at the side of the bin during the SAVH in-bin drying Experiment 2. Pred. L1 to 6: predicted moisture content values; Obs. L1 to 6: observed moisture content values, L1 = bottom, L6 = top.

of moisture were removed after 888 h of drying (18 November). The fan ran during 855 h (96.3% of the time), and supplemental heat was required during 412 h (46.4% of the time). At the end of the drying period, the observed MC of the bottom layer were 14.3% and 13.9% for the center and side of the bin, respectively, while the moisture content of the top layer was 15.8% and 14.9%. This experiment showed that the SAVH control strategy was able to equilibrate the MC of the entire grain mass close to the 15% target MC in a large farm bin (432-tonnes capacity).

Experiment 3 was carried out in Princeton, South-Western Indiana, drying white corn from 20.7% initial MC to

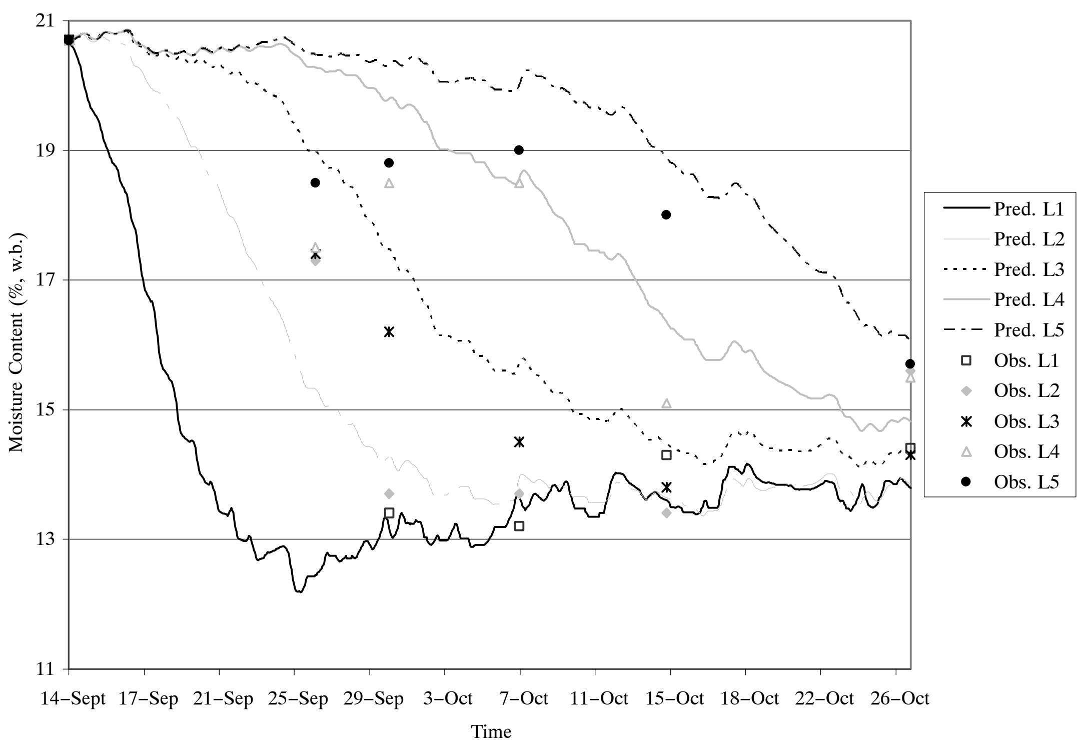

Figure 9. Predicted (Pred.) and observed (Obs.) moisture content changes in different layers at the center of the bin during the SAVH in-bin drying Experiment 3. Pred. L1 to 5: predicted moisture content values; Obs. L1 to 5: observed moisture content values, L1 = bottom, L5 = top.

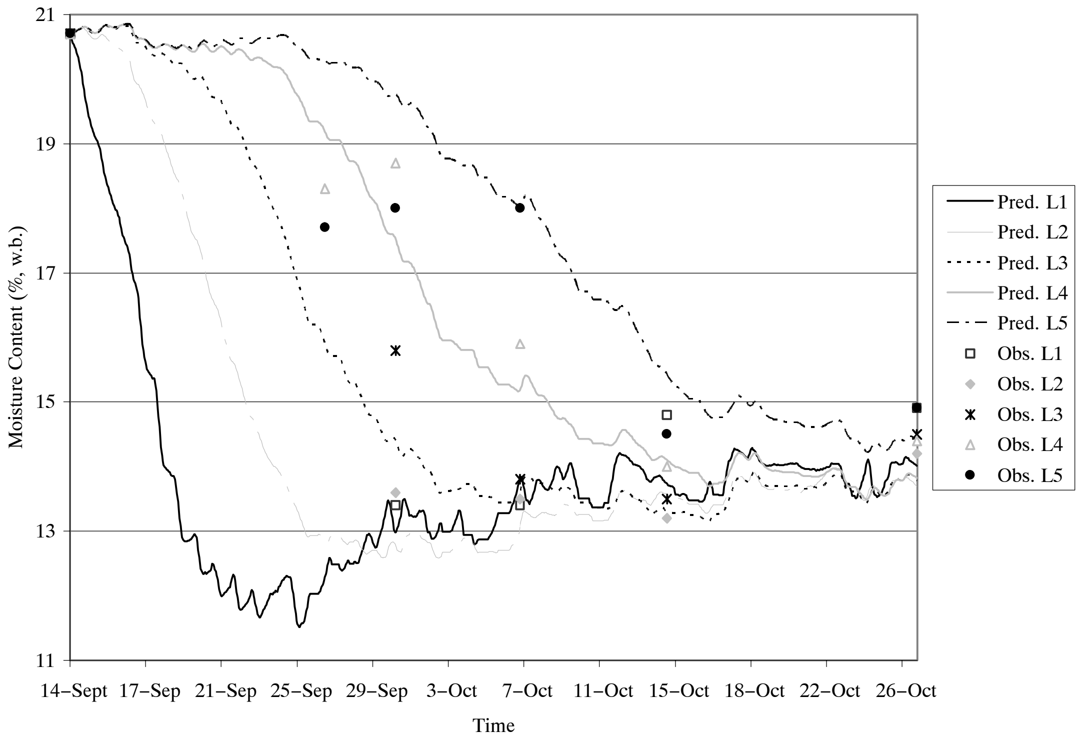

Figure 10. Predicted (Pred.) and observed (Obs.) moisture content changes in different layers at the side of the bin during the SAVH in-bin drying Experiment 3. Pred. L1 to 5: predicted moisture content values; Obs. L1 to 5: observed moisture content values, L1 = bottom, L5 = top.

14.8% final MC (0.57% point standard deviation of the final MC). In this experiment, 187 tonnes of corn were binned in an 8.2-m diameter and 5.0-m tall bin on 14 September. After binning, the grain was cored, the surface was leveled, and the airflow rate was measured for the center and side of the bin. The measured airflow rate was 0.93 and 1.26 $m^3min^{-1}tonnes^{-1}$ for the center and side, respectively. In this experiment, 5.9% points of moisture were removed after 1008 h of drying (26 October). During this period, the fan ran during 881 h (87.4% of the time), and supplemental heat was required during 462 h (45.8% of the time). At the end of the drying period, the observed MC in the bottom layers were 14.4% and 14.9% for the center and side of the bin, respectively, while the moisture content of the top layer was 15.7% and 14.9% (figs. 9 and 10). This experiment showed that the SAVH control strategy was able to equilibrate the MC of the entire mass of white corn close to the 15% target MC.

Validation of the PHAST-FDM Model for the Simulation of In-Bin Drying of Corn

The hourly weather data used to validate the prediction of MC change with the PHAST-FDM model was collected either from the SAVH control system implemented during the 2004 drying season (the SAVH control system also has the capability of collecting weather data for validation of the drying model), or from a weather station located near the SAVH and CNA in-bin drying experiments. The PHAST-FDM model was fed with the same information provided to the three SAVH control system experiments during the 2004 drying season. The required parameters to run the SAVH strategy were: corn type, number and depth of layers, initial grain MC by layer, target final MC, and airflow at the center and side of the bin. The required parameters to run the CNA strategy were: corn type, number and depth of layers, initial grain MC by layer, and airflow at the center and side of the bin. A total of 170 data points (corresponding to four different experiments) were used to validate the model.

Figures 2, 3, and 5 to 10 show the change in the observed and predicted MC for the different grain layers during the entire drying season for the center and side locations of Experiments 1 to 4. The overall evaluation of the MC prediction of the PHAST-FDM model versus the observed values shows that the SE was between 0.46% and 0.77% for all experiments when the entire drying season and the whole bin were considered (table 2). The AAVR indicates the average deviation between the observed and predicted values. The AAVR for the four experiments ranged from 0.34% to 0.57% for the entire bin and the entire drying season. Bartosik and Maier (2002) previously validated the PHAST-FDM model for in-bin drying of corn with the CNA and the VH strategies. The SE of this previous validation was higher, ranging from 0.6% to 1.2%. The improvement observed in this current validation most likely was related to the multiple enhancements implemented in the newer version of the PHAST-FDM model, which were previously explained in this article.

The success of the SAVH control strategy relies on the accurate prediction of the MC change in the bottom layer. The drying model incorporated into the SAVH control strategy is the same drying model as in the PHAST-FDM simulation tool. Figures 2, 3, and 5 to 10 show that the prediction of the MC was, in general, better for the bottom grain layer than for the rest of the bin (with the exception of Experiment 2). Table 2 shows that the SE for the bottom layer ranged from 0.43% to 0.61%, smaller the values for the entire bin (0.46% to 0.77%). The AAVR for the bottom layer ranged from 0.34% to 0.48%. When the entire bin was considered those values were higher (0.34% to 0.57%). This indicates

Table 2. Standard error (SE) of the residual values (observed – predicted) and average of the absolute value of the residuals (AAVR) for Experiments 1 to 4 for the whole bin and the entire drying season, for the whole bin and the last sampling date (end of drying), and for the bottom layer and the entire drying season.

	Whole Bin (Entire Season)		Whole Bin (End of Season)		Bottom Layer (Entire Season)	
Experiment	AAVR	SE	AAVR	SE	AAVR	SE
1	0.43	0.70	0.25	0.38	0.39	0.50
2	0.34	0.46	0.25	0.29	0.38	0.59
3	0.57	0.77	0.66	0.83	0.48	0.61
4	0.48	0.70	0.56	0.68	0.34	0.43

that the SAVH control strategy was able to predict MC changes in the bottom layer with a high level of accuracy. Based on the Thompson Equilibrium drying model theory (Thompson, 1972), the control of the MC in the bottom layer allows for the control of the MC in the rest of the grain mass. Thus, the accurate prediction of MC changes in the bottom layer allowed the SAVH control strategy to target a precise final MC for the entire grain mass by the end of the drying season. The SE for the entire grain mass at the end of the drying season for the SAVH Experiments 1 to 3 ranged from 0.29% to 0.83%, while the AAVR ranged from 0.25% to 0.66%.

CONCLUSIONS

The SAVH fan and burner control strategy was successfully implemented in three field tests during the 2004 drying season. One CNA field test was also implemented. The SAVH control strategy successfully dried wet corn (average initial MC 19.6%, 17.6%, and 20.7% for Experiments 1 to 3, respectively) close to the final target MC of 15% (average final MC of 14.8%, 14.5%, and 14.8% for Experiments 1 to 3, respectively). The variability of the final MC in the entire grain mass was also small for the three SAVH experiments (standard deviation of the MC samples at the end of drying ranged from 0.27% to 0.57% for the entire grain mass).

The SAVH control strategy identified changing weather conditions during the drying season. During the low humidity weather periods, the SAVH control strategy appropriately selected the fan operating hours that avoided overdrying of the corn. During the high humidity drying periods, in order to continue drying, the SAVH control strategy successfully used supplemental heat. The use of supplemental heat did not cause overdrying of the corn.

Compared to the CNA strategy, the SAVH control strategy avoided the overdrying of the corn when drying was carried out under the same weather conditions (average overdrying for the entire SAVH test bin was 0.2% point, compared to 1.9% points in the CNA bin).

The Post Harvest Aeration and Storage Simulation Tool – Finite Difference Method (PHAST-FDM) was validated by comparing the observed values of MC change during the four experiments implemented during the 2004 drying season with the MC change predicted by the model. The results showed that the PHAST-FDM model accurately predicted MC changes with a relatively low error (SE ranging from 0.46% to 0.77%). This SE was lower than that reported in previous validations of the PHAST-FDM model.

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