2005

Field Testing of a New Variable Heat Low Temperature In-Bin Drying Control Strategy

Ricardo E. Bartosik, *Purdue University*
Dirk E. Maier, *Purdue University*

FIELD TESTING OF A NEW VARIABLE HEAT LOW TEMPERATURE IN-BIN DRYING CONTROL STRATEGY

R. E. Bartosik, D. E. Maier

ABSTRACT. *During the 2001 and 2002 drying seasons a new variable heat (VH) in-bin low temperature drying strategy was implemented for drying corn in farm bins. In these field tests, the VH control strategy was able to select the correct operating hours based on prescribed air equilibrium moisture content (EMC) criteria with a high level of accuracy. When the ambient conditions were too wet for drying, the VH strategy was able to add the minimum amount of heat to the drying air in order to reduce the air EMC in the plenum to the desired level. The VH control strategy successfully minimized the overdrying of the grain bottom layers while drying the wet upper layers of corn, while the simultaneously operating continuous natural air (CNA) strategy overdried the bottom layers of corn by up to 2.2 percentage points before weather conditions became sufficiently wet to recondition the corn to a final moisture content similar to the VH strategy. The stress crack level did not change during the VH and CNA drying experiments.*

Keywords. *Natural air/low temperature drying, Variable heat strategy, Corn, Drying controller.*

Demand for high quality corn by the milling and snack food industries creates opportunities for farmers to receive premiums for their food grade grains. However, processors of food grade corn, for example, require adherence to strict quality standards, including fewer than 20% stress-cracked corn. Most on-farm systems use high temperature drying with air heated to 82°C to 104°C. This often leads to overdrying, excessive levels of stress cracks, and brittleness (Watkins and Maier, 1997). The primary alternative drying process to achieve the best food corn quality is natural air/low temperature (NA/LT) in-bin drying. This involves in-bin drying of corn using airflow rates of 1.1 to 2.2 m^3/min/ton and natural air or air heated by only 3°C to 8°C.

The most important limitation of the continuous natural air (CNA) drying method is its dependence on weather conditions. When the fan is operated continuously during a "good" drying year the bottom layers of the corn overdry before the top layer drops below the safe storage moisture content (MC). This reduces the uniformity of the MC in the grain bulk. Additionally, drying with CNA cannot always be completed during the fall. After the middle of December, the drying potential of the air is too low in most parts of the Midwest. Thus, the drying fan has to be turned off and drying to the final MC must be completed in the spring. To assure that the top layer is below the safe storage MC by mid-December; supplemental heat may be needed in average and poor drying years. Supplemental heat allows LT drying to be less dependent on the weather, but it generally results in overdying of the bottom layers. Stroshine et al. (1992) clearly showed that most operators use too much heat too often, and thus lose significant amounts of water due to overdrying while paying larger than necessary energy bills. Several fan/burner control strategies have been developed to address this problem. Moreira and Bakker-Arkema (1992) identified 23 different fan and/or burner control strategies that have been proposed in the literature. This reflects the range of opinions that exists among controller manufacturers and researchers when they attempt to identify the best in-bin NA/LT drying strategy.

More recently, advancement in computer capabilities made it possible to explore more sophisticated control systems. Darby (2000) developed a new fan control method called "adaptive discounting" that targets a specific grain MC and temperature. The adaptive component sequentially propagates complete individual drying fronts through the grain bulk until the target grain condition is achieved. The discounting action monitors the air selection process and changes the set points to maximize the propagation rate.

Despite significant research efforts in the past, NA/LT in-bin drying has not been widely adopted by farmers. Reasons include the need for a reliable fan/burner control system that allows for more independence from local weather conditions, while avoiding overdrying of the bottom grain layers. To solve these problems, Saksena et al. (1998) simulated nine different NA/LT in-bin drying strategies using the Purdue University Post Harvest Aeration & Storage Simulation Tool-Finite Difference Method (PHAST-FDM) (Montross, 1997). A new variable heat (VH) control strategy was ranked first based on drying cost, dry matter loss and overdrying of the grain bottom layers compared to the target MC for two Midwest corn growing areas based on 29 years of historic weather data.

The main objectives of this study were: (1) to implement the new VH strategy to dry wet corn in farm bins, and (2) to

---

Article was submitted for review in October 2003; approved for publication by the Food & Process Engineering Institute of ASAE in November 2004.

Purdue University Agricultural Research Programs, Manuscript No. 17359.

The authors are **Ricardo E. Bartosik, ASAE Student Member,** Graduate Research Associate, and **Dirk E. Maier, ASAE Member Engineer,** Professor, Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, Indiana. **Corresponding author:** Dirk E. Maier, Ag. and Bio. Engineering Bldg., 225 South University St., West Lafayette, IN 47907; phone: 765-494-1175; fax: 765-496-1115; e-mail: maier@purdue.edu.

evaluate the performance of the VH control strategy on the basis of: a) ability for selecting/conditioning the drying hours according to the prescribed criteria, b) change in the MC of the grain during the drying process, and c) effect of the drying process on the quality of the grain.

COMPONENTS OF THE VARIABLE HEAT CONTROL SYSTEM

The key components of the VH fan and burner control system developed and utilized in this study were (fig. 1): (1) the weather station with temperature and relative humidity sensors, 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 VH fan and burner controller software; and (4) the computer and VH controller software. The code to run the VH drying system controller was written in LabVIEW 6.0 (National Instruments, Austin, Tex).

THE VARIABLE HEAT STRATEGY

The selection of the quality of the ambient air for drying was based on the EMC of the ambient air (EMC_a). Solving the Modified Chung-Pfost equation (Pfost et al., 1976) for MC_D and using the T_a and RH_a, the EMC_a was computed as:

$$EMC_a = MC_D = B - (A \times \ln(-(T + C) \times \ln(RH))) \qquad (1)$$

where RH is the relative humidity (decimal); T is the temperature (°C); MC_D is the moisture content (decimal, d.b.); and A, B, and C are product constants (*ASAE Standards*, 1996).

The EMC_D was converted into EMC percent wet basis (EMC_W) as:

$$EMC_W = \frac{EMC_D}{1 + EMC_D} \times 100 \qquad (2)$$

The first step in the VH strategy decision tree was to segregate the quality of the ambient air into three groups or regions: (1) air too dry, with risk of overdrying of the bottom layers; (2) air with suitable conditions for drying "as is;" and (3) air too wet for drying (fig. 2).

The ambient air quality selection procedure was as follows: (1) if the EMC_a was below the EMC_L, then the quality of the air fell in Region 1 (reject), thus the fan was turned off so no air blew into the bin to avoid overdrying of the bottom grain layers (fig. 2); (2) if the EMC_a was in between EMC_L and EMC_H, then the quality of the air fell in Region 2 (use "as is") and the fan was turned on; and (3) if the EMC_a was above the EMC_H, the air was too wet to dry grain (Region 3, condition) and it had to be conditioned to the operator selected EMC_H. The determination of suitable EMC_L and EMC_H set points was a key criterion for this strategy, because these two values determined the quality of the air selected. The appropriate EMC_L and EMC_H values depended upon the weather pattern of each geographic location, initial and final grain MC, and airflow rate. Thus, site-specific simulation work was required to determine the ideal EMC_L and EMC_H set points (Bartosik and Maier, 2003). During the 2001 drying season 13% EMC_L and 18% EMC_H set points were used. However, for the 2002 drying season more extensive simulation work determined that 12% EMC_L and 15% EMC_H set points were more appropriate.

During the conditioning mode, when the quality of the air fell in Region 3, the burner was turned on and some heat was added to the ambient air, reducing the EMC_P to the EMC_H. A numerical routine was developed to find the T_p that would reduce the EMC in the plenum to just below the EMC_H (Bartosik, 2003). This plenum temperature was called the burner set point (BSP).

Once the VH controller obtained the BSP, it was sent to the fan/burner board as the new burner set point temperature. The fan/burner board automatically controlled the burner to closely regulate the T_p around the BSP. Whenever the T_p was below the BSP, the board fired the burner. The fan-burner

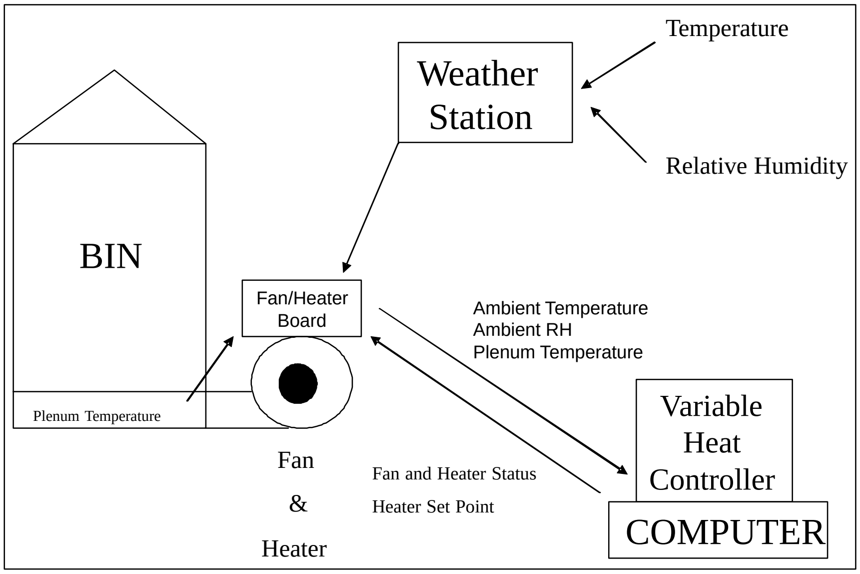

Figure 1. Diagram of the main components of the variable heat fan and burner control system and the flow of information among them.

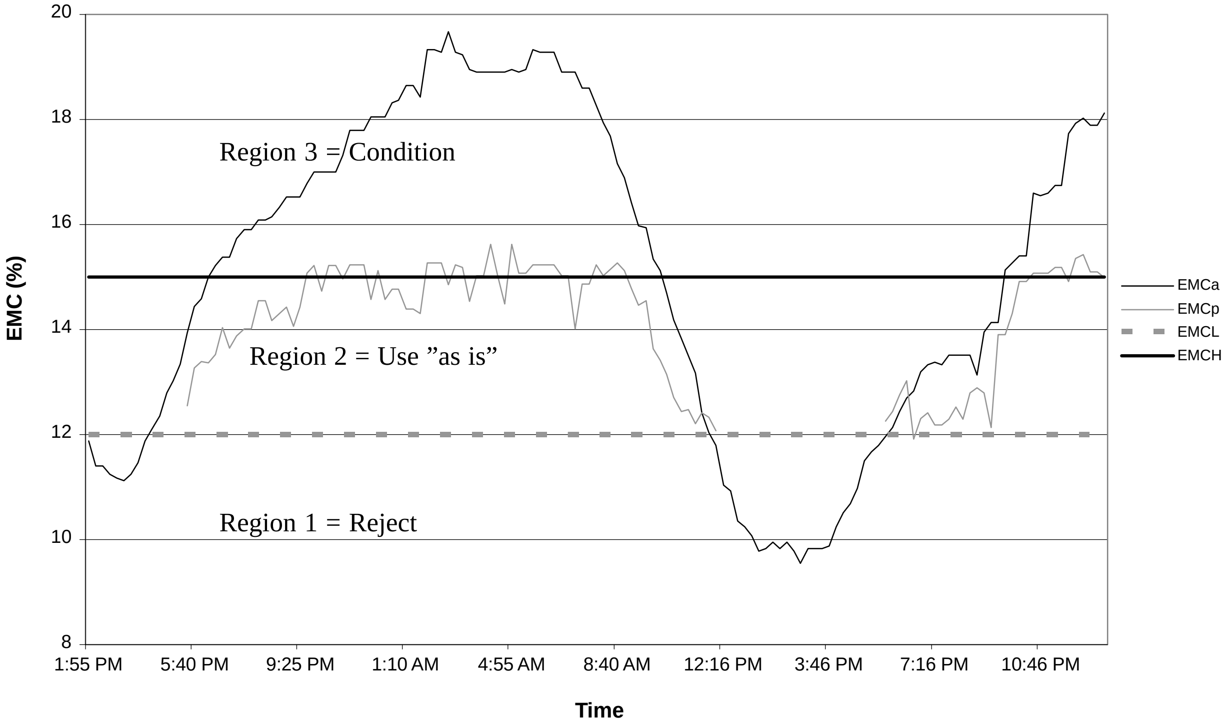

Figure 2. Ambient EMC (EMCa), lower and upper EMC set points (EMCL and EMCH), plenum drying air EMC (EMCp), and regions determining decision rules for the VH strategy.

board monitored the T_p through a temperature sensor located in the bin plenum below the drying floor. Once the burner fired, the T_p increased. A typical high-low cycling approach was utilized to modulate the T_p around the BSP. This approach turned the burner on and off to maintain the plenum drying air temperature within the temperature differential (ΔT) range provided by the operator. For example, for the ideal BSP of 20.4˚C and a temperature differential of 1.1°C, the burner fired when the plenum temperature dropped below 19.3°C (20.4°C - 1.1°C = 19.3°C), and was turned off when the plenum temperature reached 21.5°C (20.4°C + 1.1°C = 21.5°C). Thus, the plenum drying air temperature was allowed to oscillate ±1.1°C around 20.4°C.

IMPLEMENTATION OF THE VH SYSTEM IN FARM BINS

During the 2001 and 2002 drying seasons, four VH drying experiments (Experiments 1, 3, 4, and 5) and one CNA drying experiment (Experiment 2) were carried out in West Lafayette (West Central Indiana), Princeton (Southwestern Indiana), and Shelbyville (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.). Table 1 summarizes the key information for each one of these experiments. Bins were probed with a standard torpedo probe every 0.91 m (i.e., 0, 0.91, 1.83, 2.74 m, etc.) below the grain surface, and at two locations: in the center and near the sidewall. The final target grain MC of each experiment was 15%. The quality of the grain was quantified in terms of MC, grain composition (oil, protein, and starch), and stress cracks. The grain MC was determined with a calibrated GAC-2100 analyzer (Dickey-John, Auburn, Ill.). Grain composition was determined with a calibrated NIRT machine (Infratec 1229 Grain Analyzer, Eden Prairie, Minn.). Stress cracks were quantified by candling individual kernels placed germ down over a light source. For each sample, 100 corn kernels were classified as having none, single, double, or multiple (checked) cracks (GIPSA, 1997). Statistical analysis of all quality data was performed with the SAS software package (SAS 9.0, SAS Institute Inc., Cary, N.C.). Statistically significant differences were determined using the general linear model (GLM) procedure. Differences were considered statistically significant when the p-value was <0.05 (5%).

AIR SELECTION

The VH control strategy was able to select the correct operating hours based on the prescribed air EMC criteria. When the EMC_L was set at 12% to avoid overdrying of the bottom layers, the average EMC of the discarded air (air which fell in Region 1) ranged from 10.7% to 12.3% (fig. 3, "EMC_a R.1" column) during the entire drying period for Experiments 3, 4, and 5. When the EMC_a was between 12% and 15% (Region 2) the average EMC_p ranged from 12.5% to 13.2% (fig. 3, "EMC_p R.2" column). For the same operating conditions, the average EMC_a was 14.5%, 14.6%, and 14.5% for Experiments 3, 4, and 5, respectively (fig. 3, "EMC_a R.2" column). This indicates that the heat added by the friction of the fan reduced the EMC_p from 1.3 to 2 percentage points in comparison with the EMC_a. When the EMC_a fell in Region 3 (EMC_a above the EMC_H of 15%), the burner added the correct amount of heat to condition the EMC_p to 15%. During this operating period the average EMC_p ranged from 13.9% to 15.1% (fig. 3, "EMC_p R.3" column), while the EMC_a ranged from 18.5% to 20.0%

Table 1. Information for the VH and CNA in-bin drying experiments implemented at on-farm locations in Indiana during the 2001 and 2002 drying seasons.

Description	Experiment				
	1	2	3	4	5
Location	W. Lafayette	W. Lafayette	Princeton	Shelbyville	Shelbyville
Year	2001	2001	2002	2002	2002
System	VH	CNA	VH	VH	VH
Grain	Regular corn	Regular corn	White corn	Regular corn	Waxy corn
EMC set points[a]	13%-18%	−	12%-15%	12%-15%	12%-15%
Bin diameter	5.48 m	5.48 m	8.23 m	10.06 m	10.06 m
Fan	CF 3 HP	CF 3 HP	CF 10 HP	CF 25 HP	CF 25 HP
Burner	146.5 kWh	−	146.5 kWh	146.5 kWh	146.5 kWh
Grain depth	3.7 m	3.7 m	4.6 m	8.2 m	7.3 m
Static pressure	498 Pa	498 Pa	747 Pa	697 Pa	1021 Pa
Airflow[b] (m^3/min/t)	1.65	1.65	1.43	0.99	0.93
Tonnes	55	55	175	308	377
Initial drying date	8 Oct.	8 Oct.	12 Sept.	17 Oct.	22 Oct.
Initial MC[c] (%)	22.7	21.8	20.5	17.2	17.6
MC range (%)	21.0-24.0	19.4-23.9	n/a	16.9-17.5	17.2-18.0
Final drying date	19 Dec.	22 Nov.	27 Nov.	26 Nov.	27 Dec.
Final MC (%)[c]	15.3	14.3	14.6	14.9	15.0
MC range (%)	14.3-15.9	14.0-14.5	14.3-15.0	14.2-15.8	14.4-15.8

[a] EMC_L and EMC_H set points.

[b] Calculated based on fan performance curve and measured static pressure.

[c] Average values.

(fig. 3, "EMC_a R.3" column). The average EMC_p of the air that was effectively used for drying consisted of the air that was used "as is" (Region 2) plus the air that was conditioned to EMC_H (Region 3). This EMC_p ranged from 13.2% to 14.6% (fig. 3, "EMC_p" column). Experiments 4 and 5 were carried out at the same location (Shelbyville, Central Indiana), while Experiment 3 was carried out in Princeton (Southwestern Indiana). Due to the different weather patterns at these two locations, differences in the EMC_a during the drying season were observed that likely influenced the

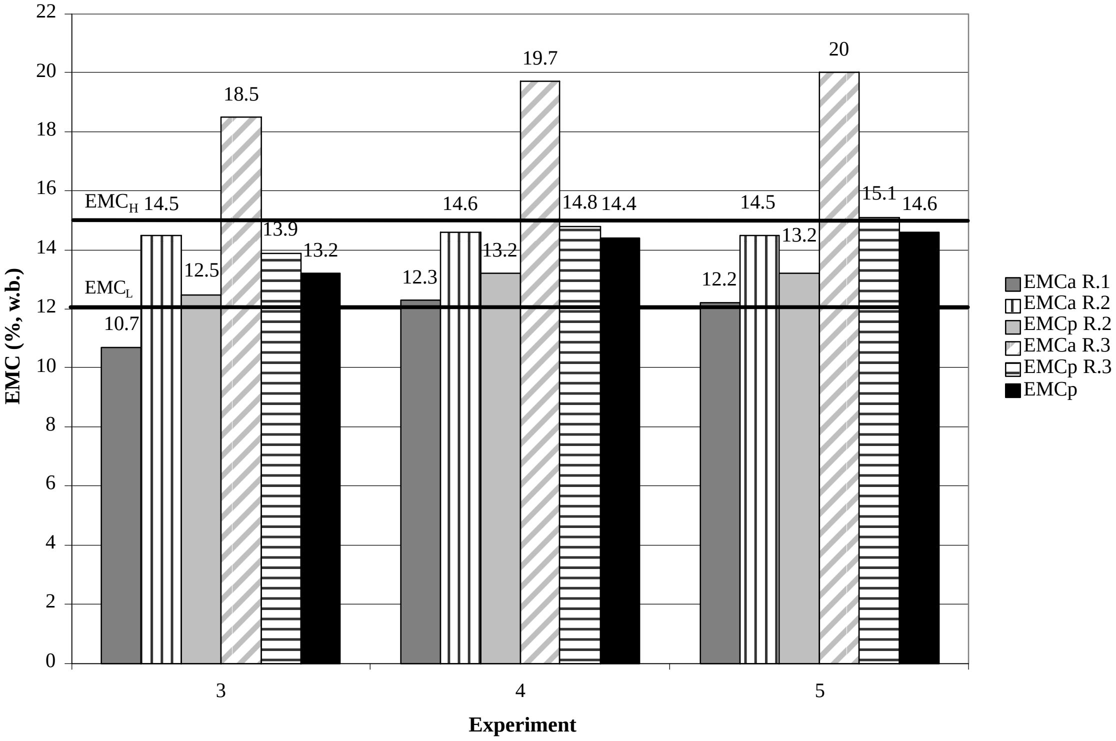

Figure 3. Average ambient and plenum EMC for Experiments 3, 4, and 5 for the periods in which the air was rejected (R.1), used "as is" (R.2) and conditioned (R.3). Ref.: EMCa = ambient EMC (%, w.b.); EMCp = actual plenum drying air EMC (%, w.b.); R.1 (fan off), R.2 (fan on and burner off), and R.3 (fan and burner on) = Regions 1, 2, and 3 of the selecting and conditioning mechanism, EMCH = EMC higher limit of 15%, EMCL = EMC lower limit of 12%.

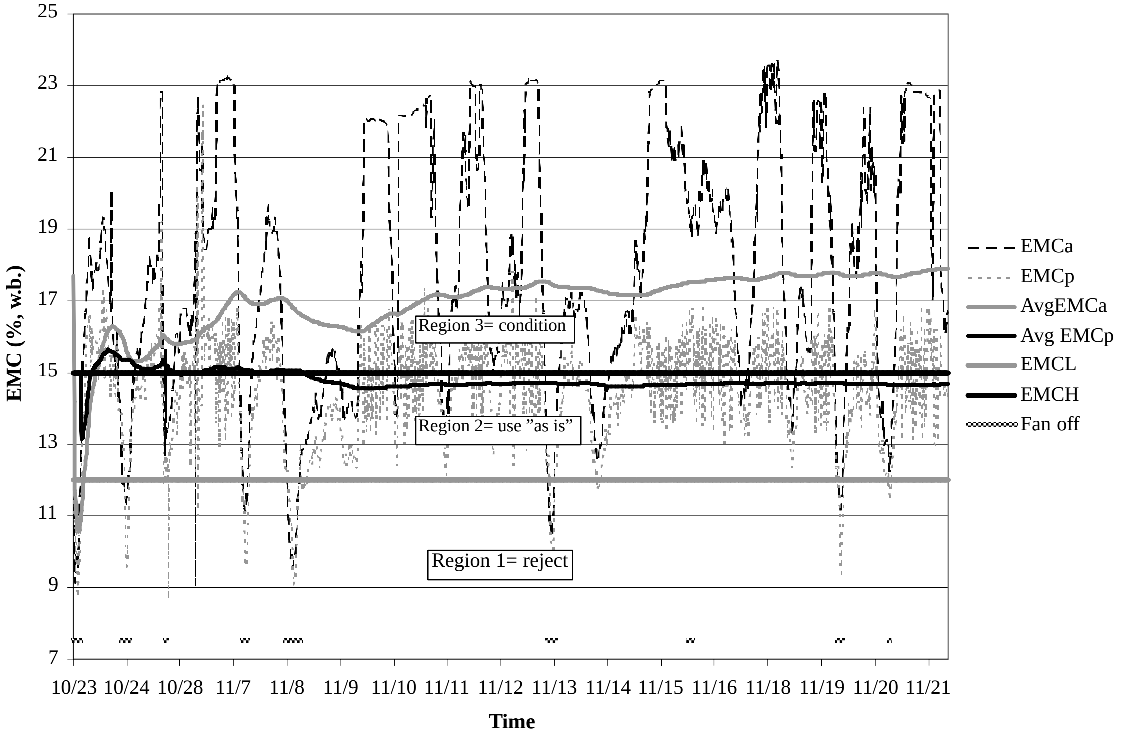

Figure 4. Ambient EMC (EMCa), cumulative average ambient EMC (Avg. EMCa), plenum drying air EMC (EMCp), cumulative average plenum drying air EMC (Avg. EMCp), EMC lower limit (EMCL), EMC higher limit (EMCH), and periods during which the fan was off (Fan off) for Experiment 5.

EMC_p. The EMC_p for Experiment 3 was on average 0.7 to 1.4 percentage points lower than the EMC_p for Experiments 4 and 5.

Figure 4 depicts the effect of the selecting/conditioning work of the VH system in Experiment 5. It can be seen that when the EMC_a was above the EMC_H, the burner was turned on, and the on-off cycling approach maintained the EMC_p oscillating around the EMC_H. This resulted in an average EMC_p of 14.6% during the entire drying period, while the average EMC_a for the same period was too wet for drying (average EMC_a about 18.0%). Figure 4 also shows the periods during which the EMC_a was below the EMC_L, and the fan was off to avoid the overdrying of the grain bottom layer (fan off-line).

PLENUM DRYING AIR TEMPERATURE

The temperature increase due to the burner confirmed that the VH system is indeed a low temperature drying system. The average T_p increase relative to T_a was 4.2°C, 3.7°C, and 3.4°C for Experiments 3, 4, and 5, respectively (table 2, "T_p-T_a" column).

The VH burner controller was able to closely maintain the BSP in the plenum (table 2, "BSP-Tp" column). For Experiment 4, the actual temperature in the plenum was as close as 0.1°C (1.4°C s.d.) to the BSP. For Experiment 5, the difference between T_p and BSP was 0.3°C (1°C s.d.), and for Experiment 3 the difference between the T_p and BSP was slightly larger, i.e., 1.2°C (2.4°C s.d.).

CHANGES IN GRAIN MC DURING THE DRYING PERIODS

In the VH experiments (Experiments 1, 3, 4, and 5), different types of corn (regular yellow dent, white, and waxy) were dried from an initial MC ranging from 17.2% to 22.7% to a final MC ranging from 14.6% to 15.3%. The final target MC for all the experiments was 15%. The VH strategy minimized the overdrying of the grain bottom layers during the entire drying period. Figure 5 shows that as early as 1 November the bottom layer of Experiment 1 had dried to 14.4%. Subsequently, the VH controller reduced the MC of the upper layers while the MC of the bottom grain layers fluctuated between 14% and 15%. The same results were observed in VH Experiments 3 to 5 (figs. 7-9). In these experiments, the MC of the grain bottom layers stabilized between 14% and 15%, while drying progressed in the upper layers. Contrasting these results, the CNA strategy (Experiment 2) caused overdrying of the bottom corn layers. Figure 6 shows that between 1 November and 15 November the corn at 1.83, 2.74, and 3.05 m (6, 9, and 10 ft) below the surface reached MC values as low as 12.7%. However, as the drying season progressed later into the fall, weather conditions turned wetter and the grain in the bottom layers gained

Table 2. Average values for the difference between the burner set point temperature and the actual plenum drying air temperature ($BSP-T_p$) and for the difference between the actual plenum drying air temperature and the ambient temperature (T_p - T_a) for Experiments 3, 4, and 5.

Experiment	BSP - T_p[a]	T_p - T_a
3	-1.2	4.2
	(2.4)	(2.4)
4	-0.1	3.7
	(1.4)	(1.6)
5	0.3	3.4
	(1.0)	(1.5)

[a] Temperature values are in °C. Standard deviation in brackets (s.d.).

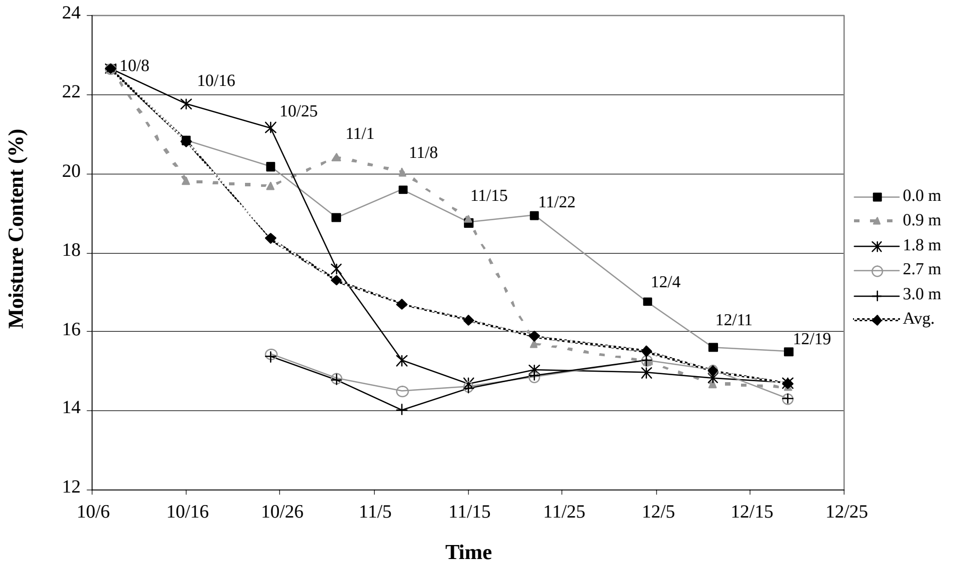

Figure 5. Moisture content (%) of corn near the wall for depth 0 to 3.0 m (0 to 10 ft) during Experiment 1 (VH strategy).

sufficient moisture to reach 14.0% by the time the experiment was completed. For some regions of the country it would be reasonable to expect an increase in the humidity conditions of the ambient air as drying progresses into the fall. However, implementing a strategy to overdry the grain bottom layers first to rewet them later is not considered a reliable drying control approach, unless the controller has the capability of quantifying the degree of overdrying at the beginning of the season to compensate it later with the same degree of rewetting. If the weather conditions had remained dry throughout the season, the CNA experiment would have overdried the bottom corn layers. This is an important difference compared to the VH strategy, which as programmed will minimize the overdrying of the grain bottom layers regardless of the weather conditions.

GRAIN QUALITY

Even when the MC of the grain in the top layers of Experiments 1, 2, 4, and 5 was greater than 18% for more than 30 days after the beginning of drying, no grain spoilage was detected. The low temperature of the ambient air during the late drying season, the relatively aggressive use of the fan and a high airflow rate most likely prevented the formation of mold and spoilage in the top grain layers. The initial and final grain composition (measured as percentages of protein, oil, and starch) was similar for the CNA and VH strategies for the 2001 drying season (Experiments 1 and 2, respectively). It was observed that the protein content decreased during drying by 0.7 percentage points for Experiment 1, and 1 percentage point for Experiment 2. Similarly, the oil content decreased by 0.2 percentage points for Experiment 1 and 0.5 percentage point for Experiment 2. Due to the

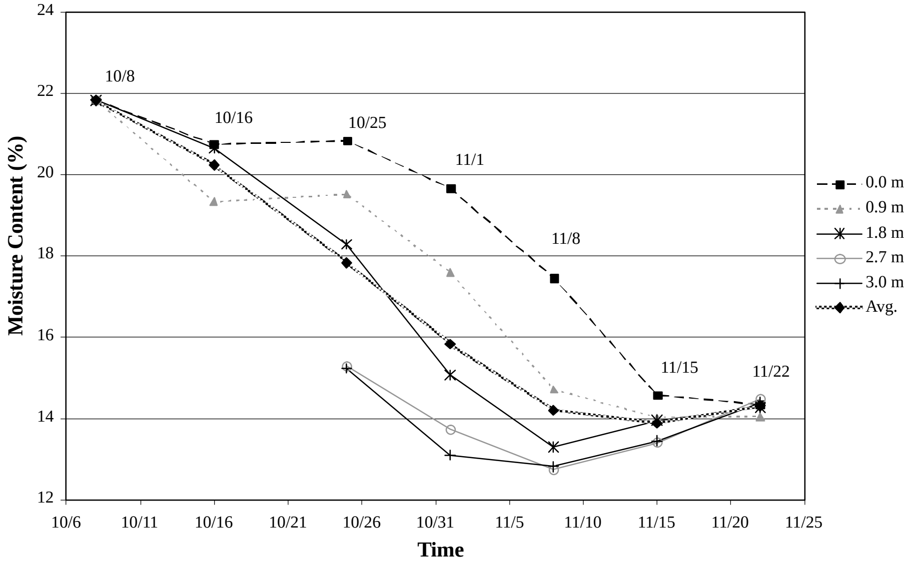

Figure 6. Moisture content (%) of corn near the wall for depth 0 to 3.0 m (0 to 10 ft) during Experiment 2 (CNA strategy).

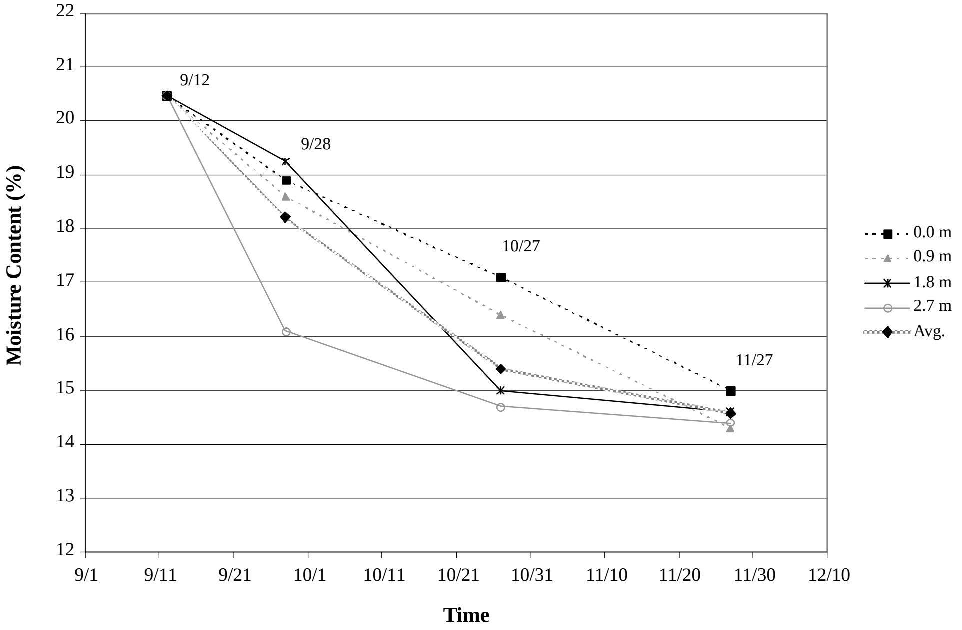

Figure 7. Moisture content (%) of white corn for depth 0 to 3.66 m (0 to 12 ft) during Experiment 3 (VH strategy).

decrease in the protein and oil contents of the samples, the relative composition of starch increased in both experiments. At the end of the drying period the starch content increased by 1.3 percentage points for Experiment 1 and 1.6 percentage points for Experiment 2 (table 3). It was estimated that a very high level of DML (1.2%) due to kernel and fungi respiration would have had to occur in these experiments to observe these decreases in oil and protein composition. Most of the research conducted in the past suggests that the expected DML value for non-spoiled grain would be below or close to 0.5% (Gupta et al., 1999). Unfortunately, DML was not quantified in these experiments, but the good condition of the grain at the end of the drying experiment and the absence of fungi suggested low biological activity in the grain bulk. Additionally, current knowledge about grain physiology indicates that carbohydrates (starch) are the primary source of energy used during seed and fungi respiration (Saul and Steel, 1966; Steel et al., 1969). Thus, it seems most likely that the observed decrease in protein and oil contents may be related to the measurement technology used to quantify composition rather than to an excessive DML. Corn composition was quantified with a NIRT machine. It has been suggested that the drop in moisture content of the grain during the drying process could affect the internal structure

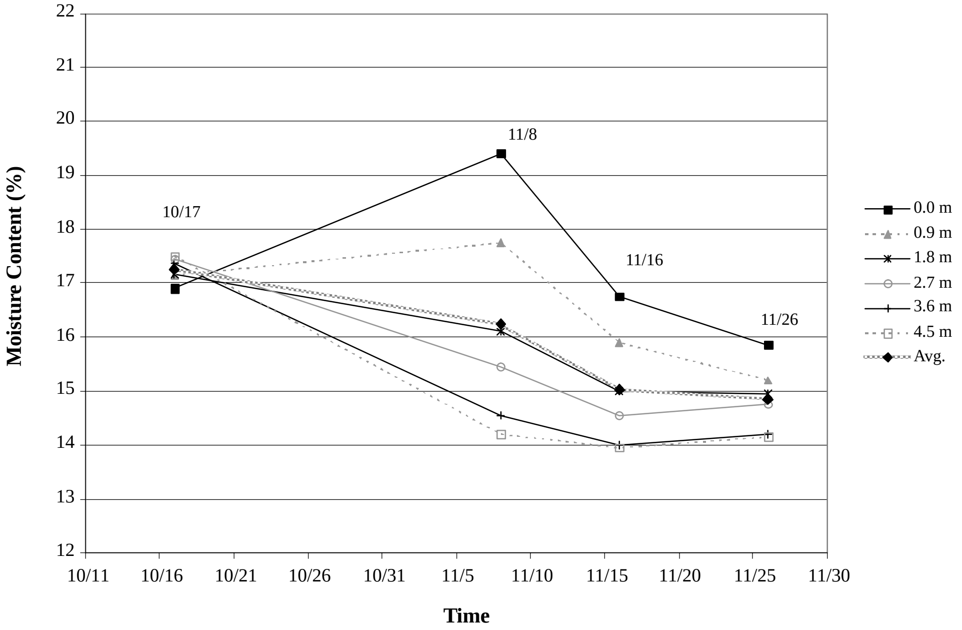

Figure 8. Moisture content (%) of corn for depth 0 to 4.57 m (0 to 15 ft) during Experiment 4 (VH strategy).

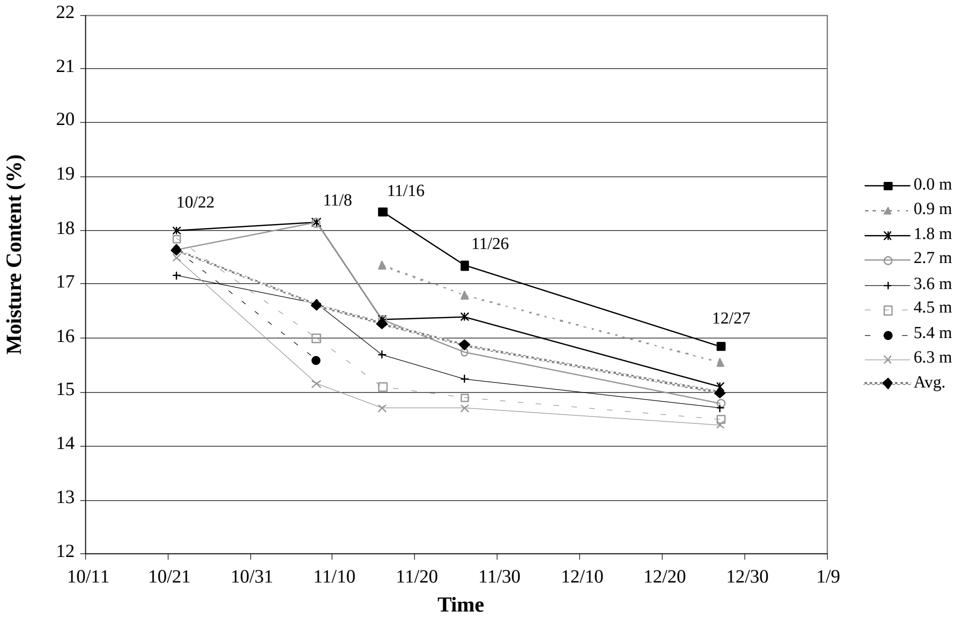

Figure 9. Moisture content (%) of corn for depth 0 to 6.40 m (0 to 21 ft) during Experiment 5 (VH strategy).

of the grain (Hamaker, 2004). When the corn kernel loses moisture, starch granules and the protein matrix in the endosperm rearrange slightly. As a result, refraction properties of the whole grain could change and affect the NIRT quantification of each component. To further explore this observation, on-going research at Purdue University focuses on quantifying DML during drying. In addition, samples of corn are being analyzed for composition with wet chemical laboratory techniques, and results will be compared to the NIRT composition data.

In 2001, corn was received with a relatively high stress crack level from the field compared to the typical level of less than 5% (Maier, 2004). The average percentage of stress-cracked grain was 14% and 11% for the VH and CNA experiments, respectively. Table 4 shows the stress crack levels at different depths and for different sampling dates for the VH and CNA strategies (Experiments 1 and 2, respectively). No differences were found in the percentage of stress-cracked kernels when comparing strategies, grain depths, and sampling dates (p-values greater than 0.05, table 5). This indicates that when compared to the CNA strategy, the VH strategy had no deleterious effect on the physical quality of the grain.

Table 4. Average stress crack percentages for different sampling dates and grain depths for Experiments 1 and 2.

Depth m (ft)	Date		
	08 Oct	15 Nov	22 Nov
Experiment 1 (VH)			
0 (0)	9	6	20
0.91 (3)	12	12	13
1.83 (6)	14	12	10
2.74 (9)	17	14	12
3.05 (10)	17	14	13
Average	14	12	13
Experiment 2 (CNA)			
0 (0)	10	10	15
0.91 (3)	13	9	10
1.83 (6)	12	13	7
2.74 (9)	8	18	13
3.05 (10)	13	21	15
Average	11	14	12

Table 3. Average grain composition values of protein, oil, and starch at different sampling dates for Experiments 1 and 2.[a]

Strategy	Date		
	08 Oct.	22 Nov.	17 Jan.
Protein			
VH	7.8	7.2	7.1
CNA	7.8	6.8	6.8
Oil			
VH	4.7	4.7	4.5
CNA	4.7	4.2	4.2
Starch			
VH	72.6	73.6	73.9
CNA	72.7	74.5	74.3

[a] Protein, oil, and starch contents are expressed on a 15% MC wet basis.

CONCLUSIONS

- The objectives proposed in this research were accomplished by implementing the VH fan and burner control strategy in three different locations in Indiana (West Lafayette, Princeton, and Shelbyville) and evaluating its performance to dry wet corn.

Table 5. P-values for stress cracks comparing drying strategies (VH vs. CNA), sampling dates, and grain depths.

Variable	Effect	p-value
Stress crack	Strategy[a]	0.67
	Depth[b]	0.18
	Date[c]	0.96

[a] Effect of the in-bin drying strategy on the quality parameter.
[b] Effect of the grain depth on the quality parameter.
[c] Effect of the sampling date on the quality parameter.

- The variable heat (VH) control strategy was able to select the correct operating hours based on the prescribed air equilibrium moisture content (EMC) criteria with a high level of accuracy. The average EMC of the ambient air discarded by the VH control system was below or slightly above the lower EMC set point of 12% (10.7%, 12.3%, and 12.2% for VH Experiments 3, 4, and 5, respectively). The average EMC in the plenum when only the fan was working (ambient EMC between 12% and 15%) was 12.5%, 13.2%, and 13.2% for VH Experiments 3, 4, and 5, respectively. During the time the burner was on (ambient EMC above 15%), the average plenum EMC was 13.9%, 14.8% and 15.1% for VH Experiments 3, 4, and 5, respectively.
- The VH control system demonstrated that it was indeed a low temperature drying system. It added the minimum amount of heat to the drying air in order to reduce the air EMC in the plenum to the desired level. The average temperature increase to condition the plenum EMC to 15% ranged from 3.4°C to 4.2°C for all VH experiments.
- The cyclical on-off operation of the low pressure LP burner demonstrated the ability to closely regulate the drying air temperature in the plenum. For three VH experiments (Experiment 3 to 5), the actual temperature in the plenum was as close as 0.1°C and as far as 1.2°C from the ideal temperature.
- The VH control strategy successfully minimized the overdrying of the bottom layers while drying the wet upper layers of corn. In VH Experiment 1, the moisture content (MC) in the bottom layers fluctuated between 14% and 15%, while in Experiment 2 the simultaneously operating continuous natural air (CNA) strategy overdried the bottom layers of corn by up to 2.2 percentage points before weather conditions became sufficiently wet to recondition the corn.
- The initial and final grain composition (measured as percentages of protein, oil, and starch) was similar for the CNA and VH strategies. The stress crack level was relatively high from the field (around 12%) on 2001 but did not change due to the drying treatments.

ACKNOWLEDGEMENTS

The authors thank Mr. Bob Townsend, Mr. Larry Yerk, Mr. and Mrs. Wil Coer, and the staff of the Purdue University Agronomy Center for Research and Education, specifically Mr. James Beaty III and Mr. Steve Zacharias, for their valuable cooperation during the experimental drying tests. The financial support and the donation of the fans and burners by The GSI Group, Assumption, Ill., through Mr. Gene Wiseman and Mr. Dave Andricks, and the technical support through Mr. Gary Woodruf and Mr. Randy Sheley were much appreciated.

REFERENCES

ASAE Standards, 43rd Ed. 1996. D245.4. Moisture relationships of plant-based agricultural products. St. Joseph, Mich.: ASAE.

Bartosik, R. E. 2003. Implementation and evaluation of a new variable heat fan and burner in-bin drying control strategy. M.S. thesis. West Lafayette, Ind.: Purdue University.

Bartosik, R. E., and D. E. Maier. 2003. Validation and application of the variable heat in-bin low temperature drying control strategy. ASAE Paper No. 036004. St. Joseph, Mich.: ASAE.

Darby, J. 2000. Aeration control developments. In *Proc. 2000 Australian Postharvest Technical Conference*, Adelaide Convention Center, Adelaide, South Australia, Australia: CSIRO.

GIPSA. 1997. Stress crack analysis. Grain inspection book, Chapter II, Corn, 4-23. Available at http://www.usda.gov/gipsa/reference-library/handbooks/grain-insp/grbook2/bk2ch4.pdf. Accessed 20 January 2003.

Gupta, P, W. F. Wilcke, R. V. Morey, and R. A. Meronuck. 1999. Effect of dry matter loss on corn quality. *Applied Engineering in Agriculture* 15(5): 501-507.

Hamaker, B. 2004. Effect of low temperature drying on structural composition of corn. Personal communication.

Maier, D. E. 2004. On-farm handling, storage and quality. In *Corn: Origin, History, Technology, and Production*, 827-866. Hoboken, N.J.: John Wiley & Sons, Inc.

Montross, M. D. 1997. PHAST-FDM revisions. Purdue University, West Lafayette, Ind.

Moreira, R. G., and F. W. Bakker-Arkema. 1992. Grain dryer control: a review. *Cereal Chem.* 64(4): 390-396.

Pfost, H. B., S. G. Maurer, D. S. Chung, and G. A. Milliken. 1976. Summarizing and reporting equilibrium moisture data for grains. ASAE Paper No. 763520. St. Joseph, Mich.: ASAE.

Saksena, V., M. D. Montross, and D. E. Maier. 1998. NA/LT drying strategies for white corn in two corn belt locations. ASAE Paper No. 986049. St. Joseph, Mich.: ASAE.

Saul, R. A. and Steele. 1966. Why damaged shelled corn costs more to dry. *Agricultural Engineering* 47(6): 326-329, 337.

Steele, J. L., R. A. Saul, and W. V. Hukill. 1969. Deterioration of shelled corn as measured by carbon dioxide production. *Transactions of the ASAE* 12(5): 685-689.

Stroshine, R. L., B. A. McKenzie, G. Sarwar, and T. L. Thompson. 1992. Improving management of low-temperature drying of corn. TR-100445 Research Report 2782-04. Electric Power Research Institute, Palo Alto, Calif.

Watkins, A., and D. E. Maier. 1997. Thin layer drying rates and stress cracking of white food corn hybrids. ASAE Paper No. 976065. St. Joseph, Mich.: ASAE.