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Effect of Airflow Distribution on the Performance of NA/LT In-Bin Drying of Corn

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EFFECT OF AIRFLOW DISTRIBUTION ON THE PERFORMANCE OF NA/LT IN-BIN DRYING OF CORN

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ABSTRACT. *The localized concentration of fine material in the core grain mass after loading a bin causes the airflow to distribute non-uniformly. In this research, the fine material distribution in the grain mass and the air velocity at the center and periphery locations in the bin were quantified for 15 on-farm natural air / low temperature (NA/LT) in-bin drying and conditioning tests. The effect of best management practices (BMPs) (i.e., leveling the grain peak after filling the bin and coring the grain mass) on fine material distribution and/or airflow distribution were quantified. When the grain peak was not leveled, the airflow distribution resulted in a non-uniformity factor (NUF) of 89% versus 36% after leveling. The coring operation reduced the concentration of fine material at the center of the grain mass by one percentage point and reduced the NUF to −28%. The effect of BMPs on the performance of NA/LT in-bin drying systems were further investigated using simulation for four representative locations in the Midwestern Corn Belt (North Platte, Nebraska; Des Moines, Iowa; Indianapolis, Indiana; and Evansville, Indiana). The total overall drying cost savings gained from applying these simple BMPs ranged from 39% to 49%. The savings were more significant in the northern and western regions (North Platte and Des Moines) than in the southern and eastern regions (Indianapolis and Evansville).*

Keywords. *Airflow distribution, Experimental data, Fine material, Natural air / low temperature drying, Simulation.*

Natural air / low temperature (NA/LT) drying systems are characterized by the in-bin drying of grains with relatively low airflow rates (most typically from 1 to 2 $m^3\ min^{-1}\ tonne^{-1}$) and natural air or air heated up to 7°C over the ambient temperature. (Note: 1 tonne is equivalent to 1000 kg, and 1 $m^3\ min^{-1}\ tonne^{-1}$ is equivalent to 0.90 $cfm\ bu^{-1}$) The drying front moves through the grain mass at a speed that is in direct relation to the airflow rate. Thus, the higher the airflow rate, the shorter the drying time. However, Bartosik and Maier (2004) reported that the optimum airflow rate for in-bin drying was 1.11 $m^3\ min^{-1}\ tonne^{-1}$. Higher airflow rates resulted in higher drying costs, due to the extra fan power required, while lower airflow rates yielded longer drying periods. Long drying periods had different consequences, depending on the ambient temperature and moisture content (MC) of the grain. In cold regions, extending the drying period into the late fall, when the drying potential of the air was low, caused the drying costs to significantly increase. In warm regions, extending the drying period into the late fall increased the risk of spoilage in the top grain layers (Bartosik, 2005).

Given a specific fan size, the airflow rate delivered by that fan is related to the total airflow resistance in the system (resistance to the airflow passing through the airflow distribution system (ducts) or perforated floor, the grain mass, and the roof vents). The higher the resistance to the airflow, the lower the airflow provided by the fan. The distribution of air into the grain mass is also related to airflow resistance inside the grain mass. Thus, zones with higher airflow resistance have less specific airflow ($m^3\ min^{-1}\ tonne^{-1}$).

Two factors affecting the airflow resistance in the grain mass are grain porosity and grain depth (Brooker et al., 1992). Grains with lower porosity, defined as the void space between kernels in a grain mass, have higher airflow resistance. Fewer and smaller void spaces produce higher resistance than larger voids. Smaller grains, like rice and wheat, have higher airflow resistance than larger grains, such as corn and soybeans. Another factor that affects porosity is fine material concentration. Fine material occupies the void spaces in the grain mass, reducing the porosity of the grain and increasing the airflow resistance. When loading a bin through the center of the roof peak, fine material tends to concentrate in the center of the grain mass. This localized concentration of fine material causes the airflow resistance to be higher in the core than at the periphery of the grain mass (Jayas and Muir, 2002). Higher airflow resistance at the center causes the air velocity and specific airflow rate to be lower in the core than in the periphery of the grain mass.

When loading a bin from the center opening of the roof, the grain drops into the middle of the bin and spreads out towards the bin wall at the fill angle of repose, forming the grain peak. The shape of the grain peak (height/diameter ratio) is related to the repose angle of grain, which mainly depends on the MC and grain type. Peaking of grain causes the grain depth in the bin to be non-uniform. At the periphery,

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close to the bin wall, the grain depth can be from a few centimeters to several meters lower than at the center, depending on the repose angle of the grain and the bin diameter. The extra grain depth at the center of the bin causes the airflow resistance to be higher in this region of the grain mass, resulting in a lower specific airflow rate.

The design of the airflow distribution system (false perforated floor, air ducts, etc.) also has a significant effect on the distribution of the airflow in the grain mass. Sokhansanj and Haghighi (2000) showed that the drying front moved faster at the center location when drying in a bin with a partially perforated floor, while when grain was dried in a bin with a slanted perforated floor, grain at the center remained wet throughout the drying process. Bartosik (2003) reported that the drying front of several NA/LT in-bin drying experiments, using fully perforated floor bins, moved faster at the periphery than at the center. The significantly lower airflow rate measured at the center was due to a higher concentration of fine material at this location. However, the effect of fine material on airflow distribution and the effect of non-uniform distribution of airflow on the performance of NA/LT in-bin drying systems were not further explored.

The goals of this research were: (1) to quantify the non-uniform distribution of fine material and airflow rate in several NA/LT in-bin drying and conditioning systems, operated under typical on-farm conditions; (2) to quantify the effect of best management practices (BMPs) (i.e., leveling the grain peak and coring the grain mass) on airflow distribution; (3) to study the effect of non-uniform airflow distribution on the movement of the drying front; and (4) to study, using the aid of simulation tools, potential drying cost savings during the NA/LT in-bin drying of corn resulting from implementing BMPs to improve the distribution of airflow through the grain mass.

METHODOLOGY

The distribution of fine material during loading and the airflow rate in a grain mass due to fine material are typically non-uniform. For this research, it was assumed that the maximum fine material concentration was located close to the central area (core) of the grain mass, while the lowest concentration was located close to the bin wall (periphery). As a result, the specific airflow rate was considered maximum close to the bin wall and minimum close to the central area of the grain mass. Thus, the problem of continuous variation of fines concentration and airflow distribution in the grain mass was simplified by considering only the two extreme situations (i.e., core and periphery). Although some limitations apply, this assumption allowed for implementing a simple computational solution for the simulation of in-bin corn drying with non-uniform airflow rate.

The data for this study were obtained during 15 NA/LT in-bin drying and conditioning experiments carried out on four farms in Indiana during the 2003 and 2004 drying seasons. The in-bin drying and conditioning experiments started in early fall, immediately after harvest, and finished in late fall or early winter. No stirring devices were used in any experiments. Table 1 details the main characteristics of the in-bin drying and conditioning systems used. Bin size ranged from 5.5 to 10.0 m diameter, 3.6 to 9.4 m grain depth, and 56 to 480 tonnes of capacity. The fan and burner control strategies for all experiments were either continuous natural air (CNA) or self-adapting variable heat (SAVH), which is a model-based fan and burner control strategy (Bartosik, 2005). The initial moisture content ranged from 17.0% to 23.3% for the drying experiments and from 14.0% to 14.6% for the conditioning experiments. The air velocity measured at the surface of the grain mass ranged from 0.028 to 0.091 m s^{-1} at the center and from 0.064 to 0.110 m s^{-1} at the periphery.

FINE MATERIAL DISTRIBUTION IN THE GRAIN MASS

Corn samples were collected during several NA/LT in-bin drying and conditioning experiments to quantify the distribution of fine material in the grain mass. After loading the bin, samples in the center and periphery of the grain mass were collected with a vacuum probe (Port-A-Probe model S, GVS, Ltd., Prairie Village, Kansas) every 1.0 m from the surface to

Table 1. Bin dimensions and capacity, initial and final corn moisture content, type of process (conditioning or drying), fan and burner control strategy, and air velocity for the center and periphery for 15 on-farm NA/LT in-bin drying and conditioning experiments.

Experiment	Diameter (m)	Height[a] (m)	Capacity (tonne)	Moisture Content (%)		Process[b]	Control	Air Velocity (m s^{-1})	
				Initial	Final			Center	Periphery
1	10.0	8.0	480	14.0	14.0	C	Fan/burner	0.032	0.077
2	10.0	8.0	480	14.1	14.1	C	Fan/burner	n/a[c]	n/a
3	10.0	8.1	480	14.6	14.1	C	Fan/burner	0.028	0.064
4	10.0	7.7	432	17.6	14.5	D	Fan/burner	0.034	0.110
5	10.0	7.6	432	17.0	14.6	D	Fan/burner	0.058	0.075
6	5.5	3.7	58.2	21.7	13.7	D	Continuous natural air	0.060	0.087
7	5.5	3.6	57.9	21.6	14.0	D	Fan/burner	0.072	0.089
8	10.0	9.0	482	20.3	15.1	D	Fan/burner	0.062	0.089
9	10.0	9.4	482	23.3	14.1	D	Fan/burner	0.053	0.090
10	8.3	4.7	178	18.6	14.0	D	Fan/burner	n/a	n/a
11	8.3	4.7	178	18.6	13.6	D	Fan/burner	n/a	n/a
12	5.5	3.4	56.4	19.6	14.7	D	Fan/burner	0.061	0.088
13	5.5	3.4	56.4	19.6	14.1	D	Continuous natural air	0.068	0.090
14	8.3	4.9	180	20.0	15.8	D	Fan/burner	0.053	0.077
15	8.3	4.7	175	20.0	14.8	D	Fan/burner	0.091	0.068

[a] Height = grain depth at the bin wall.
[b] C = conditioning experiment, D = drying experiment.
[c] n/a = data not available.

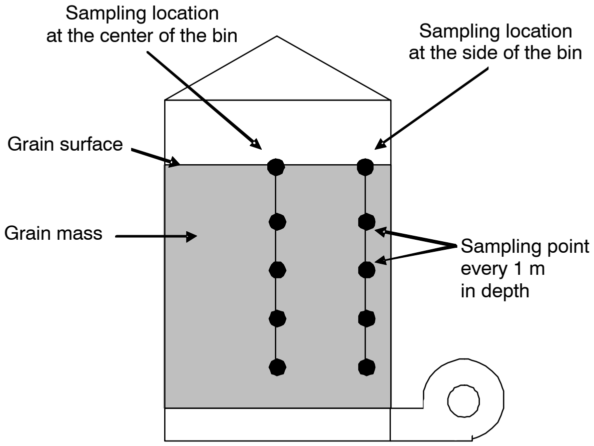

Figure 1. Schematic of the sampling locations for fine material in the grain mass.

the bottom (i.e., 0 m, 1 m, 2 m, etc.) (fig. 1). The sample size was about 400 g for each grain depth.

The corn samples were analyzed using the U.S. Federal Grain Inspection Service standard procedure for broken corn and foreign material (BCFM) composition (USDA, 2004). A 4.76 mm round-hole sieve was used to separate the BCFM from whole kernels, and the percentage of BCFM in a 250 g corn sample was determined by weight. Hereinafter, the BCFM percentage is referred to as fine material.

Figure 2. Funnel and anemometer used for measuring air velocity at different grain surface locations in the bin for natural air / low temperature in-bin drying and conditioning experiments.

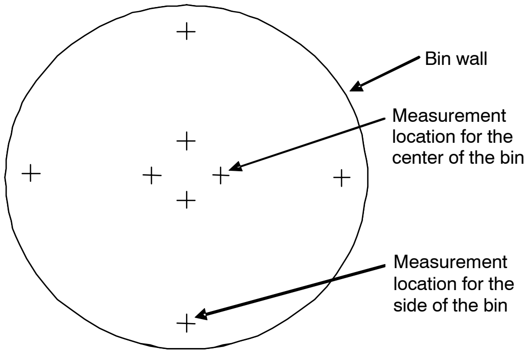

Figure 3. Schematic of the locations where air velocity was measured at the surface of the grain mass.

MEASUREMENT OF AIR VELOCITY IN THE GRAIN MASS

After the bins were loaded, air velocity was measured at the grain surface with a vane-wheel anemometer (Omega HHF91, Omega Engineering, Inc., Stanford, Conn.) and a custom-built funnel (fig. 2).

Figure 3 shows the locations where air velocity was measured in the center and periphery at the grain surface (one for each cardinal location) for the 15 NA/LT in-bin drying and conditioning experiments. The bin center corresponded to a circle of approximately 1.5 m diameter, and the periphery area corresponded to a ring approximately 1.0 m wide along the bin wall.

Air velocity exiting the grain surface cannot be directly measured by laying a vane-wheel or hot-wire anemometer on the grain surface because the air velocity is too low to measure with these devices across too small an area covered by them (a few square centimeters). Even with more sensitive devices, the variability of air velocity would require a large number of data points in order to obtain a representative average air velocity for the center and periphery locations. Instead, air velocity was measured by channeling the air through a properly designed funnel (fig. 2). The height of the funnel is 60.0 cm, 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_1) of the funnel is A_1 = 0.00456 m^2, and the bottom area (A_2) is A_2 = 0.114009 m^2. Air velocity (V_1, m s^{-1}) was measured across A_1. Airflow rate (Q, m^3 min^{-1}) is constant in the funnel, i.e., $Q_1 = Q_2$. The air velocity at the grain surface (V_2) was then computed based on the following relationships:

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

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

$$V_2 = \frac{Q_1}{A_2} \tag{3}$$

The four measured air velocities at the center of the bin were averaged and then multiplied by the bin area (A_b, m^2) to obtain an equivalent total airflow rate ($Q_{t,c}$, m^3 s^{-1}). This total airflow rate ($Q_{t,c}$) was divided by the total number of tonnes in the bin, and then multiplied by 60 s min^{-1} to obtain the specific airflow rate for the center of the bin ($Q_{s,c}$, m^3 min^{-1} tonne^{-1}). The same procedure was followed to determine the airflow rate at the periphery, based on the average air velocity measured at the periphery.

The effect of leveling the peaked grain mass after loading the bin on airflow distribution was investigated. In some on-farm experiments, air velocity data were collected both before and after the grain peak was leveled; in other on-farm experiments, air velocity data were collected only before or after the grain peak was leveled.

The effect of coring the grain mass on the distribution of fine material and uniformity of the airflow rate was also quantified. One bin filled with approximately 175 tonnes of white corn was sampled at different grain depths at the center and periphery before and after coring. Air velocity was also measured at different locations before and after coring. One load of grain (approximately 8 tonnes) was removed from the grain mass (coring of the bin), which pulled out the central column of grain above the floor well along with most of the fine material that was concentrated in that portion of the grain mass. After the coring operation, the grain surface was V-shaped at the center (a sort of inverted peak) with about 1.0 m depth.

ENHANCEMENT OF THE PHAST-FDM MODEL TO SIMULATE IN-BIN DRYING WITH NON-UNIFORM AIRFLOW

The movement of the drying front through the grain mass is directly related to airflow rate. Therefore, the MC of the grain at any time in a given layer is also a function of airflow rate. The Purdue Post-Harvest Aeration and Storage Simulation Tool − Finite Difference Method (PHAST-FDM) is a numerical model that solves the heat and mass transfer during in-bin drying and conditioning in two dimensions (x, y). It has been extensively documented by previous researchers (Maier, 1992; Adams, 1994; Zink, 1998; Bartosik, 2003) and was further refined by Bartosik (2005). To solve the problem of non-uniform airflow rate through the grain mass, PHAST-FDM simulates two grain columns: one for the core, and the other for the periphery. The heat and mass transfer equations are solved independently for each column, and the model assumes no interaction between them. PHAST-FDM accepts different non-uniformity factors (NUF) for airflow rates that can be entered by the user. The NUF was defined as the center-periphery difference with respect to the average airflow rate: (airflow periphery − airflow center / [(airflow periphery + airflow center) / 2] × 100). For instance, an NUF of 30% for an average airflow rate of 1 m s^{-1} indicates that the airflow rate is 0.85 m^3 min^{-1} $tonne^{-1}$ at the center of the bin and 1.15 m^3 min^{-1} $tonne^{-1}$ at the periphery. The PHAST-FDM model with the center-periphery differential airflow rates was validated for predicting MC changes in different grain layers for several on-farm NA/LT in-bin drying tests (Bartosik, 2005).

USING SIMULATION TO STUDY THE EFFECT OF NON-UNIFORM AIRFLOW DURING IN-BIN DRYING

Bartosik and Maier (2004) evaluated the performance of the variable heat (VH), continuous natural air (CNA), and continuous constant heat (CH) fan and burner control strategies for in-bin drying of corn from 22% initial MC to 15% final MC using simulations for four locations (Indianapolis, Indiana; Des Moines, Iowa; Lansing, Michigan; and Minneapolis, Minn.), three airflow rates (0.83, 1.1, and 1.7 m^3 min^{-1} $tonne^{-1}$), and two harvest dates (25% and 75% of the harvest period). An airflow rate of 1.1 m^3 min^{-1} $tonne^{-1}$ was identified as optimum for the VH and CH in-bin drying control strategies in all locations. The optimum airflow rate was determined based on the criterion of limiting the dry matter loss (DML) to 0.5% or less, and minimizing the total drying cost.

Bartosik (2005) studied the performance of an improved version of the VA strategy (i.e., self-adapting variable heat (SAVH)) versus the VH, CNA, and CH in-bin drying strategies for 13 locations in the Midwest. He concluded that the newly developed SAVH model-based fan and burner control strategy was the best NA/LT in-bin drying strategy for all locations.

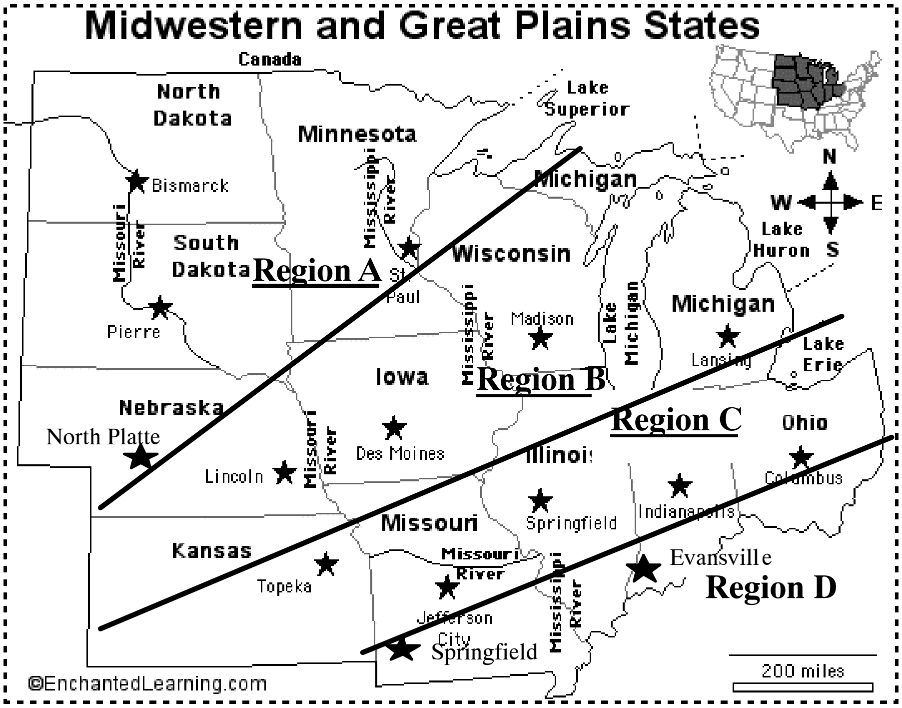

Figure 4. Midwestern and Great Plains states showing the four natural air / low temperature in-bin drying regions (adapted from MWPS-22, 1980).

The MidWest Plan Service (MWPS-22, 1980) identified four NA/LT in-bin drying regions ranging from colder (region A) in the northwestern portion of the Midwest to warmer (region D) in the southeastern portion of the Midwest. One representative location in each region was selected to conduct this investigation: North Platte (Nebraska), Des Moines (Iowa), Indianapolis (Indiana), and Evansville (Indiana) for regions A, B, C, and D, respectively (fig. 4). Forty years (1961-2000) of hourly weather data were obtained for each location (EarthInfo, Inc., available at: www.earthinfo.com).

The SAVH strategy with an airflow rate of 1.1 m^3 min^{-1} $tonne^{-1}$ was used for the simulation analysis of non-uniformity of airflow rate. Different harvest dates were considered for each region. September 15 was the harvest date for region D, October 1 for region C, October 15 for region B, and November 1 for region A. The simulation was performed for a yellow dent corn type, and the set of adsorption and desorption parameters for the equilibrium moisture content (EMC) model required to run the NA/LT in-bin drying simulations were from Bartosik (2005). The initial corn MC was 20%. The bin dimensions were 12.0 m diameter and 7.0 m tall (542 tonnes capacity). The simulation started on a harvest date representative for each location. It was concluded when the average MC at the center and periphery was equal to or lower than 15.0% and the maximum MC at the center and periphery was equal to or lower than 16.0%. For each location, an NUF level from 0% to 100% was considered. The evaluation of results was done on the basis of the maximum drying cost expected to occur with a probability of 90% (Drying Cost*) and the longest drying time expected to occur with a probability of 90% (Drying Time*). The Drying Cost* and Drying Time* were constructed using the averages and standard deviations of the drying cost and drying time of 40 years of simulation for each location and NUF level. Detailed information about how these two parameters were derived can be found in Bartosik (2005).

RESULTS AND DISCUSSION

EXPERIMENTAL RESULTS

Fine Material Concentration and Air Velocity in the Grain Mass

Table 2 shows the fine material and airflow data collected at the center and periphery (close to the bin wall) of the grain mass of 15 on-farm NA/LT in-bin drying experiments. In three experiments (experiments 1, 3, and 4), the air velocity at the grain surface was measured immediately after the bin was filled and before the grain peak was leveled. The average NUF for these three experiments was 89% (79% to 105%). In experiments 4* to 14, the air velocity was measured after the grain peak was leveled. In these experiments, the average NUF was 36% (22% to 52%). These results showed that a simple BMP, such as leveling the grain surface after loading the bin, was able to reduce the NUF by 59% (from 89% to 36%), thus improving the airflow distribution of the in-bin drying system substantially.

However, leveling the grain peak did not eliminate the non-uniform distribution of airflow in the grain mass. The 36% of non-uniformity of air velocity remaining after leveling the grain peak was most likely due to the very high concentration of fine material in the core of the grain mass. The average concentration of fine material at the center of the grain mass for experiments 1 to 14 was 1.76% (0.77% to 3.55%), compared to 0.53% (0.11% to 1.32%) at the periphery. This was a 232% higher fine material concentration in the core of the grain mass. Based on this data, it was possible to conclude that a more uniform distribution of fine material throughout the entire grain mass would be required to further improve the airflow distribution. Coring the grain mass after loading and utilizing effective grain spreaders are some of the remedial measures generally recommended to improve the fine material distribution.

Experiments 14 and 15 were conducted in two identical in-bin drying systems at the same farm. The harvest and handling operations for corn used in these two experiments were similar. In experiment 14, the grain surface was leveled

Table 2. Fine material (%) and airflow (m^3 min^{-1} $tonne^{-1}$) measured at the center and periphery (close to the bin wall) of the grain mass in 15 on-farm NA/LT in-bin drying experiments.[a]

	Fine Material (%)					Airflow (m^3 min^{-1} $tonne^{-1}$)				
	Center		Periphery		Diff.	Center		Periphery		NUF
Experiment[b]	Avg.	(s.d.)	Avg.	(s.d.)	(%)	Avg.	(s.d.)	Avg.	(s.d.)	(%)
1	1.21	(0.76)	0.39	(0.24)	0.82	0.31	0.08	0.76	0.16	84
2	0.98	(0.62)	0.57	(0.33)	0.40	n/a	n/a	n/a	n/a	n/a
3	1.51	(0.99)	0.44	(0.19)	1.07	0.27	0.05	0.62	0.06	79
4	2.08	(0.55)	0.19	(0.05)	1.89	0.37	0.03	1.19	0.38	105
4* L	n/a	n/a	n/a	n/a	n/a	0.65	0.05	1.04	0.14	47
5 L	1.09	(0.29)	0.11	(0.05)	0.98	0.63	0.12	0.82	0.10	25
6 L	3.55	(0.90)	1.32	(0.80)	2.23	1.47	0.09	2.13	0.05	37
7 L	2.23	(0.79)	0.93	(0.17)	1.30	1.77	0.12	2.19	0.10	22
8 L	0.93	(0.35)	0.15	(0.10)	0.78	0.60	0.09	0.87	0.02	36
9 L	0.77	(0.29)	0.12	(0.07)	0.65	0.52	0.03	0.88	0.04	52
10 L	2.99	(2.13)	0.89	(0.55)	2.10	n/a	n/a	n/a	n/a	n/a
11 L	2.07	(2.11)	0.85	(0.17)	1.22	n/a	n/a	n/a	n/a	n/a
12 L	1.75	(0.57)	0.51	(0.25)	1.24	1.54	0.10	2.22	0.09	37
13 L	1.25	(1.37)	0.42	(0.16)	0.83	1.72	0.17	2.30	0.10	29
14*1, L	2.27	(0.92)	0.54	(0.37)	1.73	0.96	0.47	1.39	0.20	37
15*1, L, C	1.27	(0.53)	0.56	(0.23)	0.71	1.69	0.33	1.27	0.07	−28

[a] Avg. = average value; (s.d.) = standard deviation; Diff. = difference between the average values at the center and periphery; and n/a = data not available.

[b] * = air velocity data measured after grain surface was leveled; *1 = identical bins at the same farm, loaded with corn harvested and handled under similar conditions; L = bin leveled after loading; and C = bin cored after loading.

by hand after filling the bin. In experiment 15, the bin was cored after the loading operation was completed, which resulted in an inverted peak at the center (approximately 1 m deep). The fine material concentration at the periphery in experiments 14 and 15 was similar, i.e., 0.54% and 0.56%, respectively. This was an expected result because the coring operation should not affect the fine material concentration at the periphery. On the other hand, the fine material concentration at the center of the grain mass was 2.27% in experiment 14 versus 1.27% (1.00% point lower) in experiment 15.

Even though the coring operation in experiment 15 was not sufficient to eliminate all fine material at the center of the grain mass, a substantial improvement in the fine material distribution was achieved. When compared to the non-coring experiment (experiment 14), the center-periphery difference in fine materials was reduced from 1.37 percentage points to 0.71 percentage points. The inverted peak of the grain surface and the reduction of fine material concentration in experiment 15 caused the airflow resistance to decrease through the center of the grain mass. As a result, the airflow measured there was 33% higher when compared to the airflow at the periphery, i.e., 1.69 and 1.27 m^3 min^{-1} $tonne^{-1}$ of air velocity for the center and periphery, respectively. The NUF of the airflow was 37% in experiment 14, while it was −28% in experiment 15. The airflow distribution in experiment 15 was essentially as non-uniform as in experiment 14, but more air was channeled through the center in experiment 15, while more air was channeled through the periphery in experiment 14. Thus, the coring operation was indeed sufficiently effective to modify the distribution of airflow. Based on the results of experiments 14 and 15, it is hypothesized that, if the grain surface were leveled after the coring operation, or if less grain were removed during the coring operation, the NUF of experiment 15 would be closer to 0%.

The utilization of grain spreaders was not explored in this research. Investigating the effect of various models on fine material distribution and surface leveling for different bin size configurations is important and should be explored in a future study. It is presumed that an effective grain spreader would allow for a more uniform distribution of fine material throughout the entire grain mass, and would distribute the grain across the bin area better, thus reducing the “peaking” of grain. As a result, airflow distribution in the grain mass should become more uniform, improving the performance of the NA/LT in-bin drying system.

This research also did not investigate the effect of pre-cleaning grain, which would remove substantial amounts of fines from the grain mass. This would result in less airflow resistance (and thus more airflow) and, if combined with an effective grain spreader, in a better distribution of airflow. However, grain pre-cleaning is not a common practice among farmers because it results in extra cost. These costs include the operation itself (both fixed and variable including equipment and labor) and the loss of income from a reduction in the grain mass that can be sold. The U.S. Grain Standard allows for up to 3.0% of BCFM content in Grade #2 Yellow Dent Corn. In this study, only samples from the center of experiment 6 exceeded that level (table 2), yet the farmer was

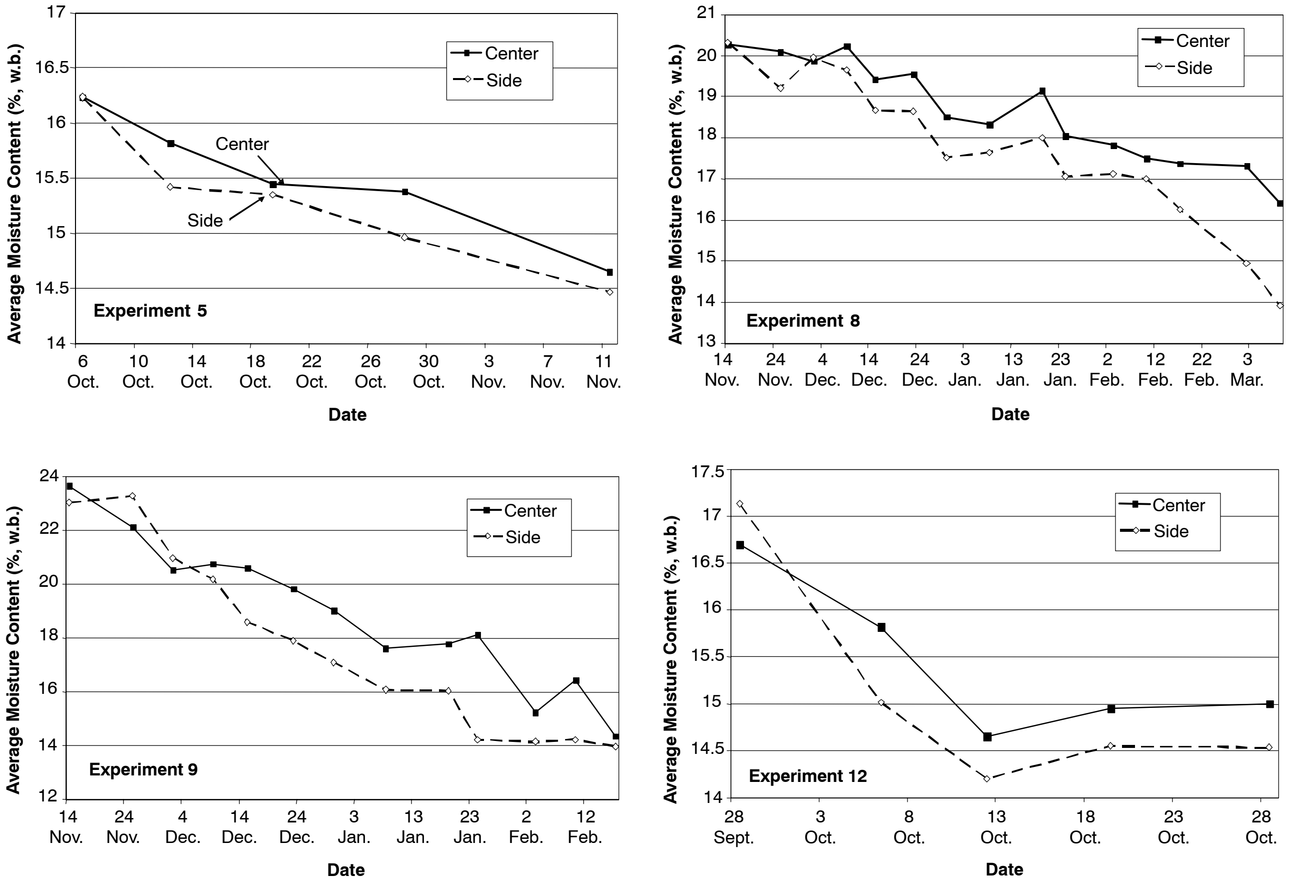

Figure 5. Change over time of the average moisture content for the center and periphery of the grain mass for four different NA/LT in-bin drying experiments (experiments 5, 8, 9, and 12 in tables 1 and 2).

not discounted at delivery because of the blending effect with lower FM corn in the periphery of the grain mass during load-out. Thus, U.S. corn farmers typically have no incentive to pre-clean grain before filling NA/LT drying bins.

Effect of Non-Uniform Airflow on the Movement of the Drying Front

Non-uniform airflow also caused drying fronts to move non-uniformly through the grain mass. Figure 5 shows the MC change for the center and periphery of the grain mass during four NA/LT in-bin drying experiments (experiments 5, 8, 9, and 12 in tables 1 and 2). (Note: The MCs shown in figure 5 are the average MCs of the center and periphery of the grain mass based on samples collected every 1.0 m from top to bottom.) At any given time during the drying period, the MC at the center was usually higher than the MC at the periphery. The difference in MC between center and periphery in each of these experiments was affected by the average airflow rate through the grain mass, the NUF of the air velocity, the initial MC of the grain, and the drying time. The particular combination of these factors caused the maximum difference in the average MC between the center and periphery locations to be 0.4, 2.5, 4.0, and 0.8 percentage points at the conclusion of drying in experiments 5, 8, 9, and 12, respectively.

Figure 5 also shows that the average MC at the periphery dropped below the target MC of 15% earlier than at the center of the grain mass due to the differential speed of the drying front between these two grain mass locations. For experiment 5, the average MC at the periphery of the bin dropped below 15% by October 29, while it took approximately seven more days to drop to the same value at the center. For experiment 8, the MC dropped below 15% by March 3 at the periphery. This experiment was concluded on March 9 while the MC at the center was still 16.4%. Most likely, it would have taken many additional drying days to reduce the average MC at the center location below 15%. In experiment 9, the MC at the periphery dropped below 15% by January 22, and 26 additional days (February 14) were required to reach 15% at the center. In experiment 12, the average MC of the grain at the periphery dropped below 15% by October 6, and five days later (October 11) the average MC of the grain at the center reached 15%.

The non-uniform distribution of air through the grain mass caused the drying front to move faster at the periphery than at the center. As a consequence, the average MC at the periphery reached the final average MC of 15% five to 26 days earlier than at the center. This difference greatly reduced the efficiency of the NA/LT in-bin drying systems because, during the extra drying time, most of the air was channeled through the periphery of the grain mass, where the grain was already dried. It could be speculated that a higher airflow at the periphery would overdry the grain in this area. However, significant overdrying was only observed in experiment 6, which was implemented with the CNA control strategy (tables 1 and 2). One possible explanation is that the model-based SAVH fan and burner controller implemented in the other experiments selected and/or conditioned the ambient air in order to equilibrate the entire grain mass to a final MC between 14% and 15%. As a result, the grain mass at the periphery reached the final MC earlier, but no significant overdrying was produced during the extra time required for drying the core of the grain mass. This is an important beneficial feature of the SAVH controller (Bartosik and Maier, 2004).

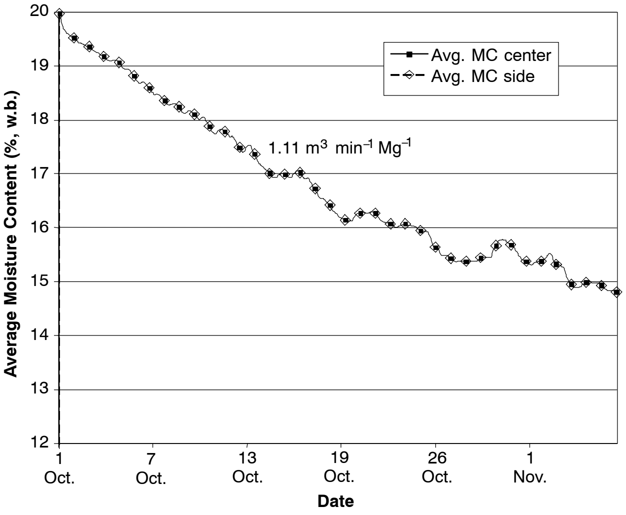

Figure 6. Average moisture content for the center and periphery of the NA/LT in-bin drying simulation experiment with a uniform airflow rate throughout the grain mass. Initial corn MC = 20%, final target MC = 15%, initial drying date = October 1, average airflow rate = 1.11 m^3 min^{-1} tonne^{-1}, and non-uniformity airflow factor = 0%.

SIMULATION RESULTS

Effect of Non-Uniform Airflow on the Movement of the Drying Front

To quantify the effect of non-uniform airflow on the movement of the drying front, the PHAST-FDM in-bin drying model was used to evaluate drying of 20% initial MC corn using Indianapolis weather conditions from the year 1961. The average airflow rate was 1.11 m^3 min^{-1} tonne^{-1}, and the initial drying date was October 1 for all simulation runs. Figure 6 shows the ideal situation, in which the airflow rate at the center and periphery of the grain mass were the same (NUF = 0%). In this ideal situation, the drying front moved at the same speed through the core and periphery and reached an average final MC of 15% by November 4.

It was previously shown (table 2) that when the grain surface was leveled after loading the bin, but no coring operation was performed, the non-uniform distribution of the fine material in the bin caused the center-periphery difference in the airflow rate to be substantial (NUF from 20% to 50%). Figure 7 represents the movement of the drying front at the center and periphery when the NUF was 40%. The higher periphery airflow rate (1.332 m^3 min^{-1} tonne^{-1}) compared to the center (0.778 m^3 min^{-1} tonne^{-1}) caused the average MC at the periphery of the bin to decrease below 15% nine days earlier (October 26) than for the ideal situation (November 4). On the other hand, the average MC at the center of the bin dropped below 15% thirteen days later (November 17) than for the ideal situation. In this example, the grain at the periphery of the grain mass reached the desired final average MC 22 days earlier than the grain at the center. This difference was similar to the difference observed for experiments 8 and 9 (fig. 5). The drying conditions in these two field experiments were similar to the drying condition investigated in this simulation, i.e., airflow rate of 0.75 m^3 min^{-1} tonne^{-1} through the center and initial grain MC of 20% and 23% for experiments 8 and 9, respectively,

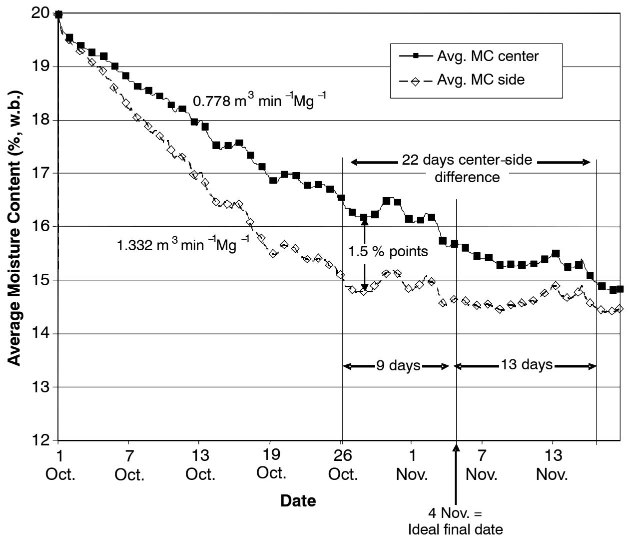

Figure 7. Average moisture content for the center and periphery of the NA/LT in-bin drying simulation experiment with non-uniform center-periphery airflow rate. Initial corn MC = 20%, final target MC = 15%, initial drying date = October 1, average airflow rate = 1.11 m^3 min^{-1} tonne^{-1}, and non-uniformity airflow factor = 40%.

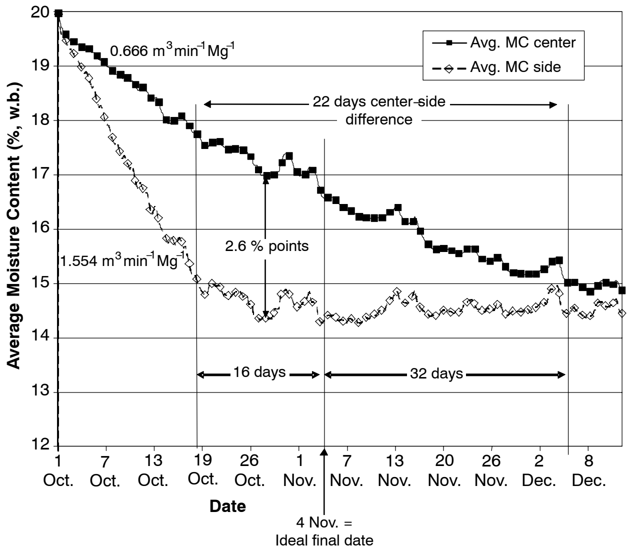

Figure 8. Average moisture content for the center and periphery of the NA/LT in-bin drying simulation experiment with highly non-uniform center-periphery airflow rate. Initial corn MC = 20%, final target MC = 15%, initial drying date = October 1, average airflow rate = 1.11 m^3 min^{-1} tonne^{-1}, and non-uniformity airflow factor = 80%.

resulting in about 25 days of difference to achieve 15% MC or less at the center and periphery. The non-uniform airflow rate also caused the MC of the grain to be substantially different during the drying process at different locations in the bin. The maximum difference in MC between the core and periphery of the grain mass during the entire drying period was 1.5 percentage points (fig. 7).

When the grain surface was not leveled after loading the bin, the difference in the center versus periphery airflow rates was from 80% to more than 100% (table 2). Figure 8 represents the simulated movement of the drying front in the bin when the NUF was 80%. The higher airflow rate at the periphery (1.554 m^3 min^{-1} tonne^{-1}) compared to the center (0.666 m^3 min^{-1} tonne^{-1}) caused the average MC at the periphery to decrease below 15% sixteen days earlier (October 19) than for the ideal situation (November 4). On the other hand, the average MC at the center of the bin did not drop below 15% until 32 days later (December 6) than for the ideal situation. In this example, the grain at the periphery reached the desired average final MC of 15% forty-eight days earlier than the grain at the center. The non-uniform airflow rate also caused the MC of the grain to be substantially different during the drying process at different locations in the bin. The maximum difference in MC between the core and periphery of the grain mass during the entire drying period was 2.6 percentage points.

Effect of Non-Uniform Airflow on the Time and Costs of In-Bin Drying

To quantify the effect of non-uniform airflow on the time and costs of in-bin drying, the PHAST-FDM simulation tool was used to compare the four locations of each Midwestern region over 40 years (1961-2000). Figure 9 shows the number of hours required to complete drying corn from 20% initial MC to a final average MC of 15% with an average airflow rate of 1.11 m^3 min^{-1} tonne^{-1} and different levels of NUF (from 0% to 100%). Bartosik (2005) showed that the geographical region had a substantial influence on the Drying Time*, increasing the number of hours required to reduce the MC of the grain mass below 15% from the southeastern to northwestern portions of the Corn Belt. The Drying Time* increased exponentially with NUF, indicating that the non-uniformity of the airflow rate caused a substantial extension of the drying period at all locations, which was more severe at higher NUFs. Additionally, the increase in Drying Time* differed with location. For the northwestern location of North Platte (Nebraska), the Drying Time* increased 150% (from 1400 to 3500 h) when the NUF of the airflow increased from 0% to 100%. For the southeastern location of Indianapolis (Indiana), the Drying Time* increased only 138% (from 1000 to 2380 h) when the NUF increased from 0% to 100%.

The extended drying times caused by the non-uniform airflow rate resulted in extra fan and burner run hours, which increased energy consumption. Thus, drying corn to a final

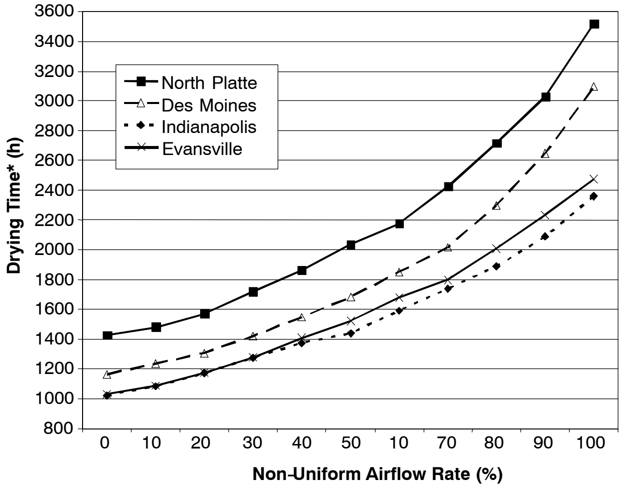

Figure 9. Number of drying hours expected to occur with a probability of 90% (Drying Time*) for NA/LT in-bin drying with a non-uniform airflow rate factor (NUF) from 0% to 100% for four different Midwestern locations. Initial average grain MC= 20%, final average grain MC = 15%, and average airflow rate = 1.11 m^3 min^{-1} tonne^{-1}.

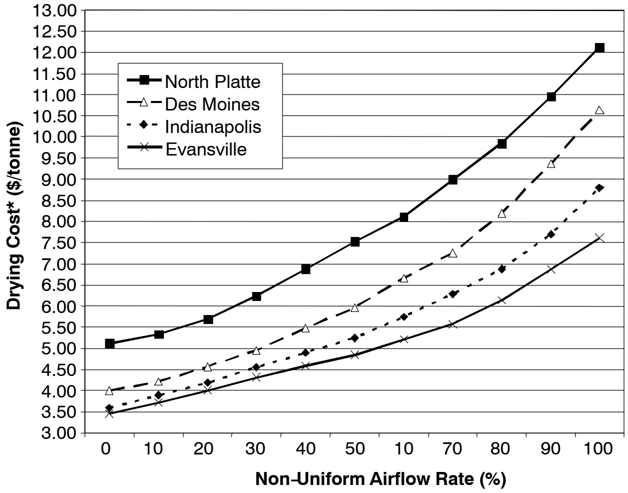

Figure 10. Drying cost ($ tonne^{-1}) expected to occur with a probability of 90% for NA/LT in-bin drying with a non-uniform airflow rate factor (NUF) from 0% to 100% for four different Midwestern locations. Initial average grain MC= 20%, final average grain MC = 15%, and average airflow rate = 1.11 m^3 min^{-1} tonne^{-1}.

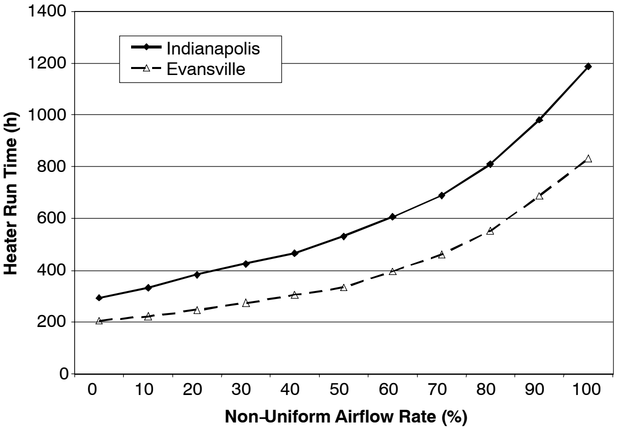

Figure 11. Burner runtime hours expected to occur with a probability of 90% for NA/LT in-bin drying with a non-uniform airflow rate factor (NUF) from 0% to 100% for Indianapolis and Evansville. Initial average grain MC= 20%, final average grain MC = 15%, and average airflow rate = 1.11 m^3 min^{-1} tonne^{-1}.

average MC of 15% was more expensive as the NUF level increased. Figure 10 shows the Drying Cost* associated with different levels of NUF. Notice that the shapes of the Drying Cost* curves of figure 10 were similar to the shapes of the Drying Time* curves of figure 9. This is because the fan and burner energy consumption are the two most important factors (the third being overdrying of the grain) affecting the Drying Cost*. Bartosik (2005) showed that Drying Cost* increased from the warmer regions of the southeast (region D) to the colder regions of the northwest (region A), which is similar to the results observed in figure 10 for North Platte (region A) and Evansville (region D).

Evansville (southwest) is an Indiana location about 290 km (180 miles) to the south and west of Indianapolis (central). Figure 9 shows that the Drying Time* for Indianapolis was the same or only slightly lower than the Drying Time* for Evansville, implying that the weather conditions for these two locations were similar. However, figure 10 shows that the Drying Cost* for Evansville was $0.50 to $1.25 per tonne lower than the Drying Cost* for Indianapolis. Figure 11 shows that although the Drying Time* was similar for both locations, drying corn under Indianapolis conditions required from 88 to 352 more burner run hours than drying corn under Evansville conditions. Thus, the relatively warmer weather conditions of Evansville required fewer burner run hours for drying corn than the relatively colder weather conditions of Indianapolis.

The Drying Cost* increased exponentially with NUF, indicating that the non-uniformity of the airflow rate caused a substantial increase in the Drying Cost* at all locations. In addition, this increase was more severe at higher levels of NUF. Additionally, the increase in the Drying Cost* differed with the location. For the northwestern location of North Platte (Nebraska), the Drying Cost* increased 133% (from $5.2 to $12.1 tonne^{-1}) when the NUF of the airflow increased from 0% to 100%, while for the southeastern location of Evansville (Indiana), the Drying Cost* increased only 117% (from $3.5 to $7.6 tonne^{-1}) when the NUF increased from 0% to 100%.

Table 3 summarizes the Drying Cost* for four levels of NUF (0%, 10%, 40%, and 80%) for four locations (North Platte, Des Moines, Indianapolis, and Evansville). The Drying Cost* for 0% NUF represents the drying cost for the ideal NA/LT in-bin drying condition (i.e., airflow rate is completely uniform in the entire grain mass), which was the lowest (fig. 10). However, based on several experimental observations, a 0% NUF is not likely a realistic expectation for in-bin drying operations. The Drying Cost* for 10% NUF represents the presumed situation in which the non-uniformity of the airflow rate is improved by utilizing an effective grain spreader, or by coring the grain mass and leveling the grain surface. This would eliminate most of the fine material concentrated in the center of the grain mass, and is considered an achievable goal for an on-farm in-bin drying operation. The Drying Cost* for 40% NUF represents the situation in which the grain peak is leveled after loading, but no further improvement with respect to the fine material distribution (and airflow rate) is implemented. The Drying Cost* for 80% NUF represents the worst-case scenario, in which the grain peak is not leveled after loading the bin.

Table 3. NA/LT in-bin drying cost ($ tonne^{-1}) expected to occur with a probability of 90% (Drying Cost*) for four levels of non-uniform airflow rate factor (NUF = 0%, 10%, 40%, and 80%) and the corresponding savings in the expected drying cost ($ tonne^{-1}) obtained from different BMPs for four Midwestern locations. Initial average grain MC= 20%, final average grain MC = 15%, and average airflow rate = 1.11 m^3 min^{-1} tonne^{-1}.

	Drying Cost* ($ tonne^{-1})				Savings in Drying Cost* ($ tonne^{-1})		
Location	0% NUF (Ideal)	10% NUF (Cored or Spread)	40% NUF (Leveled)	80% NUF (Not Leveled)	Cored or Spread	Leveled	Total
North Platte	5.12	5.34	6.87	9.85	1.54	2.97	4.51
Des Moines	3.99	4.21	5.47	8.19	1.27	2.72	3.98
Indianapolis	3.59	3.89	4.89	6.87	1.00	1.98	2.98
Evansville	3.45	3.72	4.58	6.14	0.86	1.55	2.42

Leveling the grain peak manually after loading the bin was a simple operation that caused a reduction in the Drying Cost* ranging from 25% to 33% (table 3). The effect of leveling the grain peak was greater in the northwestern region (North Platte, region A), as it decreased the Drying Cost* by \$2.97 tonne^{-1} (from \$9.85 to \$6.87 tonne^{-1}) compared to a southeastern region (Evansville, Indiana), where it decreased by only \$1.55 tonne^{-1} (from \$6.14 to \$4.58 tonne^{-1}).

When leveling the grain peak was achieved either by coring the grain mass after loading the bin or by loading the bin with an effective grain spreader, additional savings in the Drying Cost* from 18% to 22% were achieved. The effect of coring the grain mass or utilizing an effective grain spreader was greater in the northwestern region (North Platte, region A), as it decreased the Drying Cost* by \$1.54 tonne^{-1} compared to the southeastern region (Evansville, Indiana), where it decreased by only \$0.86 tonne^{-1} (table 3).

The combined effect of implementing realistic BMPs, i.e., leveling the grain peak after loading the bin, which improves the airflow distribution, either by coring the grain mass or by installing effective grain spreaders, resulted in total Drying Cost* savings of 45% (\$4.51 tonne^{-1}) for North Platte (region A), 49% (\$3.98 tonne^{-1}) for Des Moines (region B), 43% (\$2.98 tonne^{-1}) for Indianapolis (region C), and 39% (\$2.42 tonne^{-1}) for Evansville (region D) (table 3).

CONCLUSIONS

The concentration of fine material in the grain mass and the air velocity at the surface of the grain mass was measured at the center and periphery for 15 on-farm NA/LT in-bin drying and conditioning experiments. It was observed that the accumulation of fine material in the core was up to 232% higher than at the periphery. The NUF of the airflow rate was proposed as an index to quantify the effect of leveling the grain peak and coring the grain mass on airflow uniformity. It was defined as the difference between the airflow rates through the center versus the periphery of the grain mass with respect to the average airflow rate of the entire bin.

The effect of not leveling the grain peak after loading the bin caused the airflow rate to be higher at the periphery than at the center, which resulted in an average NUF of 89% versus 36% when the grain peak was leveled. The non-uniform distribution of the airflow rate required 48 more days to dry the core of the grain mass versus the periphery when the NUF was about 80% (grain peak not leveled), compared to approximately 22 days when the NUF was about 40% (grain peak leveled).

Simulation results showed that drying time increased by 150% (from 1400 to 3500 h) when the NUF increased from 0% to 100% for North Platte (Nebraska), compared to only 138% (from 1000 to 2380 h) for Evansville (Indiana), while the drying costs increased as a consequence of the extra fan and burner run hours by 133% (from \$5.2 to \$12.1 tonne^{-1}) for North Platte (Nebraska), compared to only 117% (from \$3.5 to \$7.6 tonne^{-1}) for Evansville (Indiana).

Based on the simulation results, operators of NA/LT in-bin drying systems could reduce drying costs from 25% to 33% by leveling the grain peak after loading the bin. Additional reductions in drying costs from 18% to 22% could be achieved by installing effective grain spreaders or by coring the grain mass. Savings were more substantial in the northwestern regions (North Platte, Nebraska; and Des Moines, Iowa) than in the southeastern regions (Indianapolis and Evansville, Indiana) of the U.S. Corn Belt and could easily pay back the added cost of installing an effective grain spreader or performing the coring operation.

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