

Influence of floor air entry on grain moisture content, temperature, and bulk shrinkage during ambient air in-bin drying of wheat

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Gu, D., Sokhansanj, S. and Haghighi, K. 2000. Influence of floor air entry on grain moisture content, temperature, and bulk shrinkage during ambient air in-bin drying of wheat. *Can. Agric. Eng.* 42:185-193. Wheat at 22% m.c. (w.b.) was dried using ambient air in an experimental bin with a fully perforated, a partially perforated, or a slanted perforated floor. When grain was dried in the bin with a partially perforated floor, moisture contents of the grain were distributed in such a way that higher moisture content grain was at the sides of the bin. When grain was dried in the bin with a slanted perforated floor, grain at the center of the bin remained wet throughout the drying process. Profiles of inter-granular temperature contours were similar to profiles of moisture content contours. Higher temperatures corresponded to lower moisture contents. Inter-granular air temperature remained at or near the wet-bulb temperature of the drying air until the grain moisture content decreased to 15% (w.b.). A curved grain surface resulted from uneven bulk grain shrinkage due to non-uniform airflow. At the same plenum static pressure and with the same volume of grain, air entering the bin with a partially perforated floor was about 78% of that with a fully perforated floor. **Keywords:** drying, shrinkage, airflow, moisture content, temperature, ambient air, floor, wheat.

Du blé dont le taux d'humidité était de 22% (base humide) fut séché en utilisant l'air ambiant dans des silos expérimentaux ayant un plancher entièrement perforé, un plancher partiellement perforé, et un plancher perforé incliné. Après le séchage du grain dans le silo à plancher partiellement perforé, les grains qui étaient placés sur les côtés du silo avaient la teneur en eau la plus élevée. Lors du séchage dans le silo à plancher perforé incliné, le grain au centre du silo est demeuré humide tout au long de la période de séchage. Les courbes de température entre les grains suivaient les courbes de teneur en eau des grains. Les températures plus élevées correspondaient à des teneurs en eau plus faibles et vice versa. La température de l'air entre les grains est demeurée près de ou à la température boue humide de l'air utilisé pour le séchage, jusqu'à ce que la teneur en eau du grain s'abaisse à 15 % (b.h.). Les grains avaient une surface courbe parce que, comme la circulation de l'air n'était pas uniforme, la masse de grains s'est contractée de manière inégale. Pour un même volume de grain et pour une pression statique identique dans la chambre de distribution, la quantité d'air pénétrant dans le silo à travers le plancher partiellement perforé représentait 78% de la quantité d'air pénétrant dans le silo par un plancher entièrement perforé. **Mots clés:** séchage, contraction, écoulement d'air, teneur en eau, température, plancher, blé.

INTRODUCTION

Airflow in a bin with a fully perforated horizontal floor is "uniform" because air moves in parallel paths at a uniform velocity. The airflow is one dimensional, resulting in uniform

drying of grain. Airflow in a bin with a partially perforated floor or slanted perforated floor is "non-uniform". The air travels in streamlines that are not parallel and the air velocity varies along the flow path. Non-uniform airflow results in non-uniform drying.

Experimental data on ambient air in-bin grain drying with non-uniform airflow are limited. Studies were conducted mostly in small scale experimental bins. Hukill and Shedd (1955) conducted experiments on oat drying in a quonset type storage with a central ventilating plenum tunnel. The drying process was indirectly monitored using relative humidity sensors buried in the grain. A photographic technique was employed by Ives et al. (1959) to determine the drying zones in the on-floor drying of white sorghum. Williamson (1965) conducted drying experiments with slightly heated air in a bin with lateral ducts. Small open weave net sample bags were filled with grain and placed at several depths in the bin. Non-uniformity in moisture content was observed laterally and vertically. Smith et al. (1992a, 1992b) conducted drying experiments in a partially perforated grain bin for seven days. Little agreement was found between the simulated and the experimental moisture contents.

Theoretically, the drying of a column of grain is considered to be an adiabatic process, and thus the heat required for evaporation of the moisture is supplied solely by the drying air. During the adiabatic drying process, the temperature of the drying air approaches its wet-bulb temperature, while the humidity ratio increases (Brooker et al. 1992). Although the actual drying process is not completely adiabatic, the inter-granular air temperature during ventilation may be used as an indication of the drying progress.

Temperatures within ventilated grain bulks under uniform airflow have been studied experimentally (Sorenson et al. 1967; Sutherland 1975; Ingram 1976, 1979) and theoretically (Sutherland et al. 1971, 1983; Bowden et al. 1983; Hunter 1988). Most of the findings, as pointed out by Sanderson et al. (1988), are based on computer simulations with limited data from field experiments.

Boyce (1965, 1966) and Sanderson et al. (1988) conducted drying tests in small beds of grain under uniform airflow. They successfully identified the location of the drying front by measuring air temperatures. An attempt was made by Robinson (1992) to control a high temperature grain dryer under uniform airflow using temperature sensors.

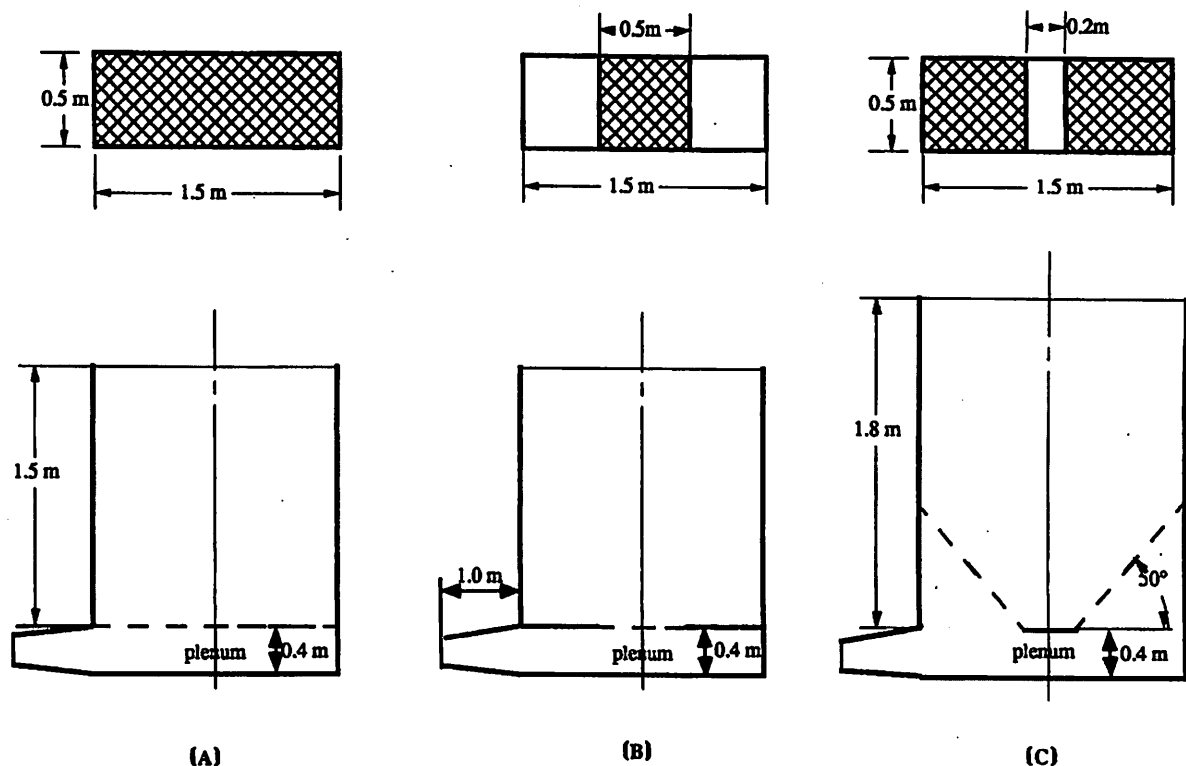


Fig. 1. Schematic diagram of the test bin with floor A (totally perforated), floor B (partially perforated), and floor C (slanted perforated).

OBJECTIVE

The objective of this experimental study was to investigate the general trend of ambient air in-bin drying of grain and its shrinkage under non-uniform airflow, as affected by floor configuration. The feasibility of using temperature to monitor the progress of ambient air in-bin drying with non-uniform airflow was also tested.

MATERIALS and METHOD

The experimental set-up consisted of a ventilated grain bin container and instruments for measuring static pressures, grain temperatures, and inter-granular air velocities. The container, 1.5 m in length and 0.5 m in width, was made of plywood with angle iron reinforced corner joints.

Figure 1 shows three floor configurations installed in the bin: a totally perforated (floor A), a partially perforated (floor B), and a slanted perforated (floor C). The floors were made of steel sheets with circular perforations giving an open area of about 13%. The grain in the bin was 1.5 m high for floors A and B; and 1.8 m high for floor C, which resulted in the same volume of grain for each floor type. A 150-mm circular duct was the transition that connected a variable speed centrifugal blower to a 0.4 m deep plenum under the perforated floor.

Hard red spring wheat, cultivar 'Katepwa', cleaned of chaff and fines, was used in the tests. Bulk density of the grain was 813 kg/m^3 and kernel density was 1435 kg/m^3 . Moisture content of the grain was 8.7% (w.b.). A predetermined amount of water was sprayed and mixed with the wheat mass to increase its

moisture content to 20 - 22% (w.b.). The moistened wheat was then stored in sealed containers at room temperature for 24 h before being removed from the containers for re-mixing. The re-mixed grain was stored for an additional 24 h before a test. The grain moistening procedure was followed for each of the tests.

Drying tests were conducted with each floor configuration. Once one of the floor configurations was installed in the experimental bin, the bin was filled with the moist grain to the predetermined height, and the top surface was leveled. A test lasted 5 to 8 d.

A probe of 25 mm diameter was devised to take samples from the grain bed for moisture content determination. The probe could capture about 15 g of grain per sampling. The grain was sampled once a day from 25 uniformly distributed locations throughout the bin (Figs. 2 and 3). Moisture content of the samples was determined using the convection oven method specified by ASAE Standard S352.2 (ASAE 1994a).

Inter-granular temperatures were measured hourly using 39 type J, 24 gauge thermocouples (0.5 mm). Thermocouples were distributed evenly throughout the grain bed in the bin with floor B or floor C (Figs. 4 and 5). The distribution of thermocouples in the bin with floor A was the same as that in the bin with floor B. Shrinkage was determined daily by measuring the grain height during drying at 5 equally distanced points from the bin central line to a resolution of 1 mm. Static pressures and air velocities were measured daily [see Gu et al. (1996) for details].

The dry and wet-bulb temperatures of drying air were recorded throughout all of the tests. Air velocity approaching the drying bed was set at about 0.04 m/s as recommended by

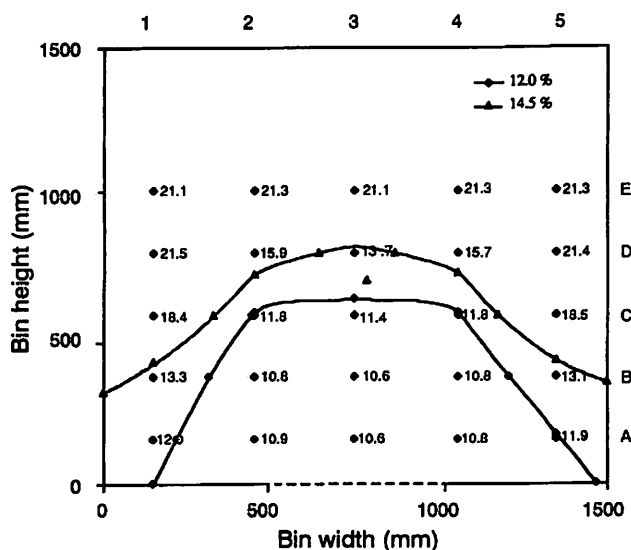


Fig. 2. Measured moisture contents and two iso-moisture lines in the bin with floor B after 91h drying (average m.c. of 15.2% w.b.).

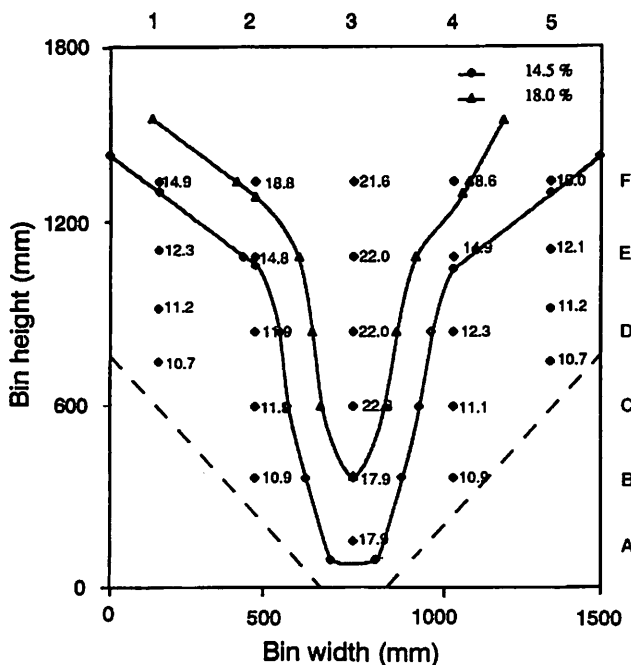


Fig. 3. Measured moisture contents and two iso-moisture lines in the bin with floor C after 65 h drying (average m.c. 15.3% w.b.).

Brooker et al. (1992). In accordance with ASAE Standard D272.2 (ASAE 1994b) and the volume of grain mass in the bin, the static pressure in the plenum was adjusted to and kept at about 300 Pa by adjusting the variable speed blower. Actual airflow rate to the drying bed was measured once a day by a Pitot tube grid installed in the air duct.

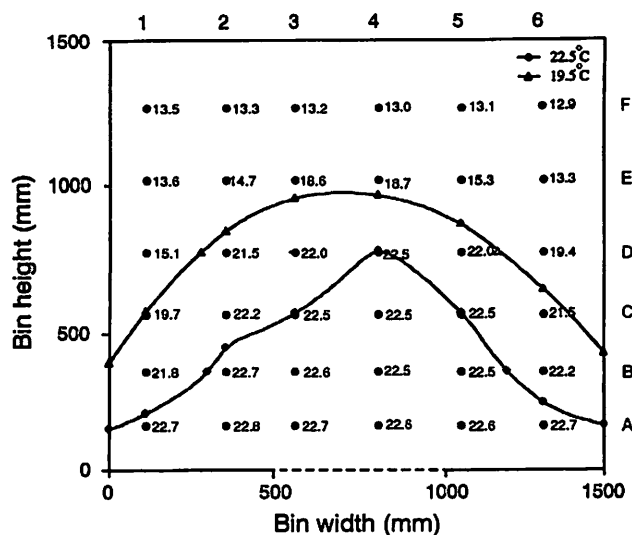


Fig. 4. Measured temperatures in the bin with floor B after 91 h drying.

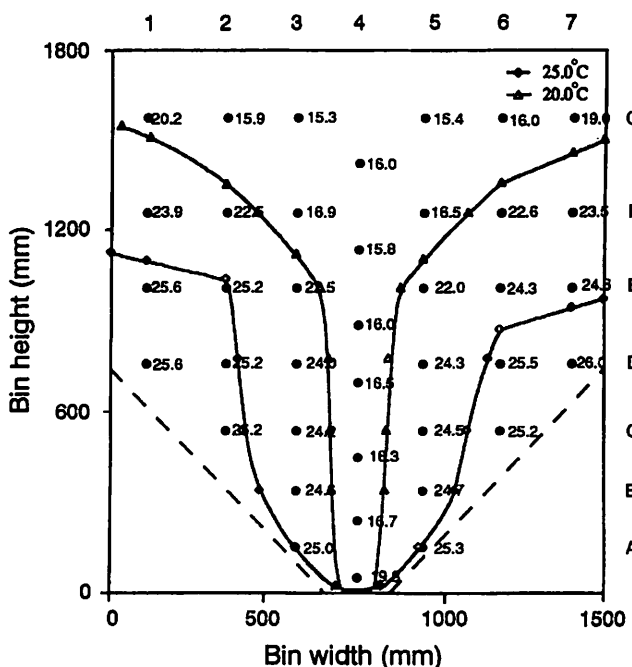


Fig. 5. Measured temperatures in the bin with floor C after 65 h.

RESULTS

A preliminary test was conducted in the bin with floor A to check equipment and instrumentation and to develop a procedure to determine the duration of a test. Grain moisture contents and inter-granular temperatures during the test were measured and analyzed. The data (Gu 1994) showed that when the difference between the temperature of the drying air in the plenum and the temperature at a location in the drying bed approached zero, the difference between the moisture content at that location and the equilibrium moisture content of grain at the corresponding air condition was less than 1.0 percentage of

Table I. Initial grain conditions before tests and condition of drying air during tests.

Floor	Initial grain conditions			Drying air during tests	
	M _i (% w.b.)	T _i (°C)	H _i (m)	Temperature (°C)	RH (%)
A	20.6 (0.3)*	31.9 (0.9)	1.44	26.8 (0.4)	30 (2)
B	22.5 (0.2)	30.8 (0.7)	1.50	25.3 (0.5)	32 (4)
C	22.9 (0.20)	30.1 (1.1)	1.80	25.8 (0.9)	34 (3)

* Mean (sd. dev.)

moisture content (w.b.). Based on the finding, test runs were terminated when one of the temperature readings at the top level of the grain bed approached within 0.5°C of the dry-bulb temperature of the drying air.

Three tests for each of the floor configurations were conducted. In this paper, data from one of the three tests for each of the floor configurations are discussed. Data from other tests were given in Gu (1994).

The initial grain conditions such as moisture content, M_i, temperature, T_i, and the grain bed height, H_i, for each of the tests are given in Table I. (Moisture contents in this paper are given in percent wet basis unless otherwise specified.) These initial conditions were taken immediately after a fill. Grain was carefully observed before, during, and after each test to check for any sign of mould or spoilage, and none was observed.

The average temperature of the drying air and the RH for each of the tests also are given in Table I. The drying air conditions were recorded at the beginning and during each test.

Moisture contents

Figures 2 and 3 show the measured local moisture contents of the grain in the bin with floors B and C when the average moisture content of the entire bin was about 15.3%. Two iso-moisture lines were plotted to signify the shape of the drying front.

Table II. The average moisture content of grain in the bin with floors A, B, and C.

Floor A		Floor B		Floor C	
Hours from start	M.C. (% w.b.) Average (Range)	Hours from start	M.C. (% w.b.) Average (Range)	Hours from start	M.C. (% w.b.) Average (Range)
0	20.6 (20.1 - 21.0)	0	22.5 (22.2 - 22.7)	0	22.9 (22.5 - 23.2)
24	17.9 (12.5 - 19.4)	25	20.7 (13.0 - 22.1)	17	20.1 (14.4 - 22.4)
49	15.4 (11.0 - 19.8)	49	19.3 (11.2 - 22.0)	41	17.3 (11.3 - 21.9)
80	11.8 (9.7 - 16.5)	73	17.7 (11.1 - 22.0)	65	15.3 (10.7 - 22.0)
98	10.7 (9.5 - 12.9)	91	15.2 (10.6 - 21.5)	86	13.2 (10.6 - 21.9)
115	10.0 (9.5 - 11.0)	121	13.5 (10.5 - 21.4)	112	12.0 (10.3 - 21.4)
		145	11.8 (10.1 - 18.6)		
		168	10.6 (9.6 - 13.5)		

The iso-moisture lines were approximately horizontal in the bin with floor A. The locations near the bin wall dried faster than the central region of the bin (15.4% at the center versus 14.8% at the sides). This was probably due to a higher airflow at the sides. Nevertheless, the difference among the central locations and the side locations was not more than 1 percentage moisture content.

The iso-moisture lines curved upward in the centre of bin with floor B and curved downward in the centre of the bin with floor C. For the two bins, moisture contents at a given grain bed height varied considerably. With floor B, drying at the sides of the bin was slow. For example, the grain at the off-center location A1 took about 136 h, while the grain at the center location A3 took about 68 h to dry from 22.3 to 11.0%. When the bin average moisture content was 12%, the maximum variation of moisture content at the top sampling height varied from 12.4 to 18.6%.

With floor C, large moisture gradients existed in all directions. For example, when the bin average moisture content was 15.3%, the maximum variation of moisture content at level E varied from 12.1 to 22.0% (Fig. 3). When the bin average moisture content decreased to 12%, the maximum variation of moisture content at level E, varied from 11.0 to 21.4%. A core of high moisture content grain was formed during drying at the center of the bin. The moist core persisted even when the average moisture content was lower than 12%. An extra 45 h was required to dry the core from 21.4% to 14.8%. The average moisture content was 11.7% when the core temperature was 14.8%. Table II lists the average moisture content of grain in the bin with floors A, B, and C. To remove 11 percentage points of moisture content from the moist grain over the entire bin, it took 115 h with floor A, more than 145 h with floor B, and about 112 h with floor C.

Temperature

The iso-temperature lines drawn from measured data in the bin with floor A were parallel to the bin floor. There were some variations at a given height, but these variations were within 1°C. Temperature distributions in the bin with floors B or C were not uniform but generally symmetric (Figs. 4 and 5). Temperatures indicated in Figs. 4 and 5 were measured at the same time as the measured moisture contents discussed in the previous section. The temperatures at the sides of the bin with floor B took a longer time to show a change in the temperature of the drying air than those in the centre of the bin. For instance, after 145 hours of drying, the temperature at the top centre of the drying bed was 21.5°C, while at the top sides, the temperature was 15.8°C. As a comparison, a low temperature zone was observed at the center of the bin

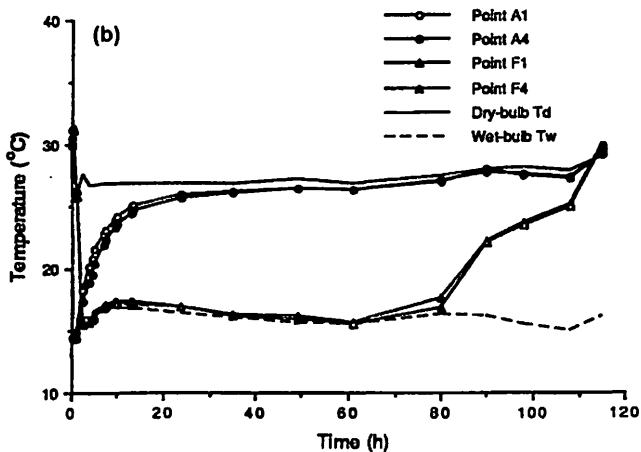
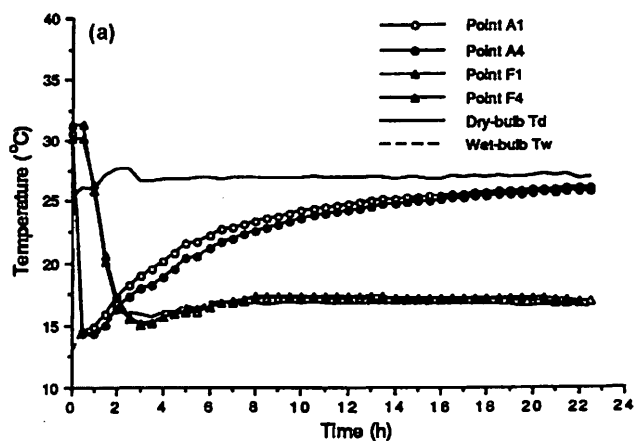


Fig. 6. Temperatures at selected points in the bin with floor A during the first day (a) and during the entire drying period (b).

with floor C after a period of drying. This zone gradually shrank to a small core as drying progressed, which corresponded to the high moisture content grain in the bins. Temperature difference among the top sampling points after 112 h drying was about 10°C. In general, all of the temperature profiles were similar to their corresponding moisture content profiles.

Figures 6, 7, and 8 show the temperatures at selected points in bins with floors A, B, and C. Each figure shows the temperature plot of the first day of a test and the daily temperatures during the entire test. The dry-bulb and wet-bulb temperatures of the drying air in the plenum also are plotted on the graphs.

In Fig. 6, points A1 and A4 were located at the bottom and points F1 and F4 were located at the top of the bin with floor A (similar to Fig. 4). Figure 6a shows that the dry-bulb temperature of the drying air, initially at 26°C, increased to about 27°C during the first 3 h and remained constant thereafter. The wet-bulb temperature of the drying air remained at about 17°C after a period of 4 to 6 h of fluctuations. The grain at the lower parts of the bin (A1 and A4) decreased from the initial temperature of 32°C to the wet-bulb temperature in less than 1 h and then gradually increased to near the dry-bulb temperature within the next 20 h. The temperatures at upper

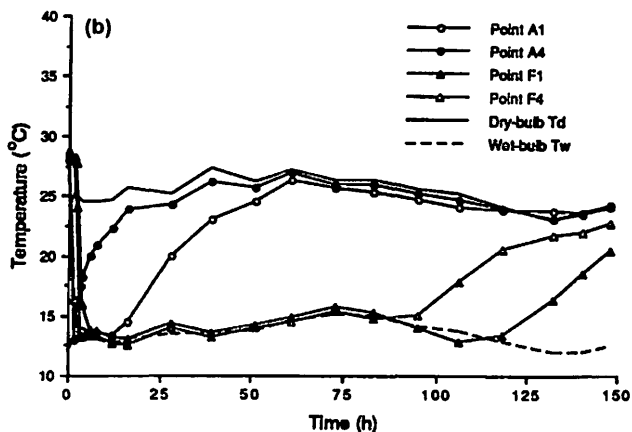
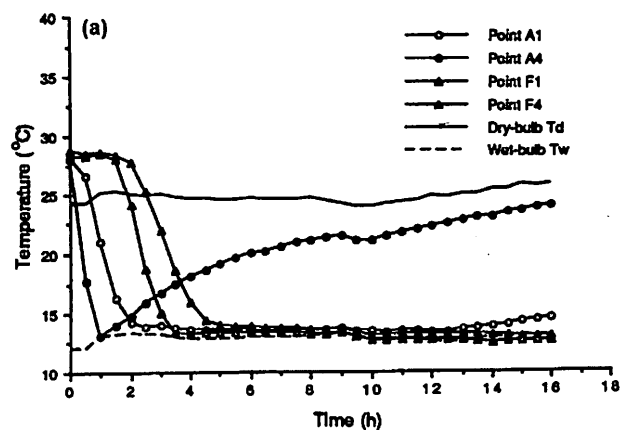


Fig. 7. Temperatures at selected points in the bin with floor B (see Fig. 4) during the first day of drying (a) and during entire drying period (b).

levels (points F1 and F4) decreased to within 0.5°C of the wet-bulb temperature in 3 h and remained there. After 80 h of ventilation, the grain at the upper level started to dry and the temperature began to rise to the dry-bulb temperature (Fig. 6b).

Figure 7 shows that in the bin with floor B the time for the temperature of the grain to drop from the initial temperature 27°C to the wet-bulb temperature of the drying air varied from point to point. Figure 7a shows that the temperature at the central bottom point A4 took about 1 h to drop to the wet-bulb temperature of the drying air. Side bottom point A1 took more than 2 h to drop to the wet-bulb temperature and stayed there for about 12 h. For the grain at the upper level, the temperature at the central point F4 took about 3 h and the side point F1 took about 5 h to decrease to the wet-bulb temperature of the drying air, and then remained at the wet-bulb temperature for 90 and 120 h, respectively (Fig. 7b).

Temperatures in the bin with floor C (Fig. 8) had a non-uniform response similar to those in the bin with floor B. Grain at the side of the bin cooled much quicker than that at the central part of the bin. The cooled grain at the centre of the bin (points A4, G4) did not approach the wet-bulb temperature of the drying air as closely as that experienced in either bin with floors A or B, which indicated that grain at the central area of the bin may not have received enough drying air. Another

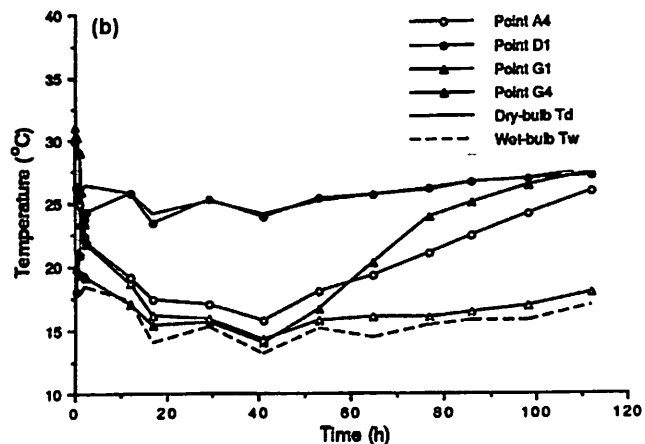
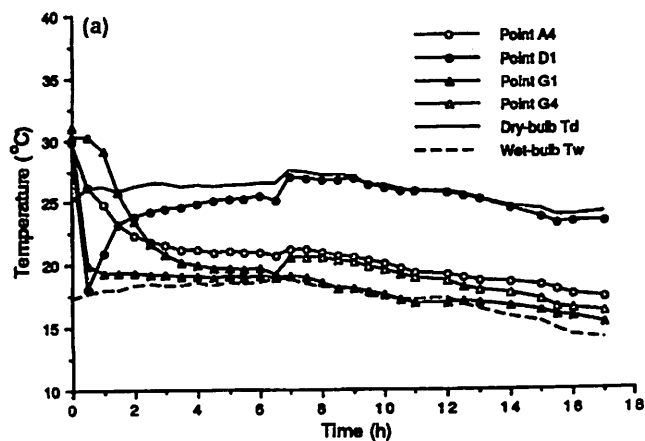


Fig. 8. Temperatures at selected points in the bin with floor C (see Fig. 5) during the first day of drying (a) and during entire drying period (b).

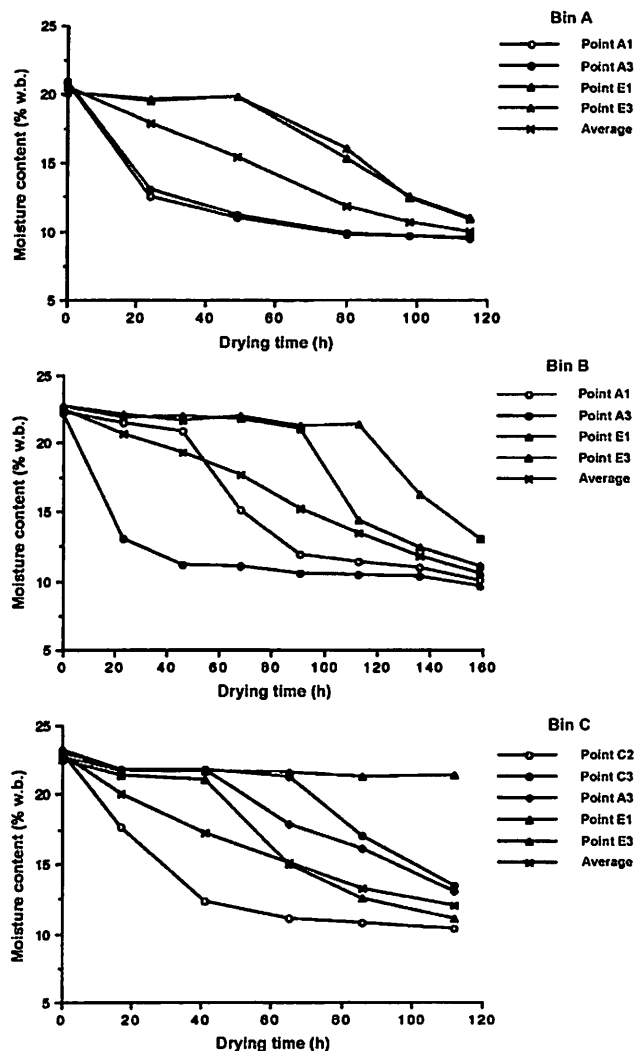


Fig. 9. Moisture contents at selected points in the bin with floors A, B, and C (see Figs. 2 and 3) versus drying time.

observation was that the temperature at the central upper part (point G4) eventually reached and remained at the wet-bulb temperature (Fig. 8b); correspondingly, the moisture content of the grain at this point remained wet, at about 22% (w.b.).

Relationship between temperature and moisture content of the grain

Figure 9 shows the moisture contents at select points in the bin with floors A, B, or C. Referring to the data in Figs. 6, 7, or 8, it was found that the temperature of the grain remained at or near the wet-bulb temperature of the drying air until the moisture content of grain was lower than 15%. The temperature of the grain started to increase and approached the dry-bulb temperature of the drying air after this time.

The test in the bin with floor A had shown that when the temperature at a location within the grain bed was near the drying air temperature, the moisture content of the grain at that location approached the equilibrium moisture content of the drying air condition. Figure 10 is a plot of the difference

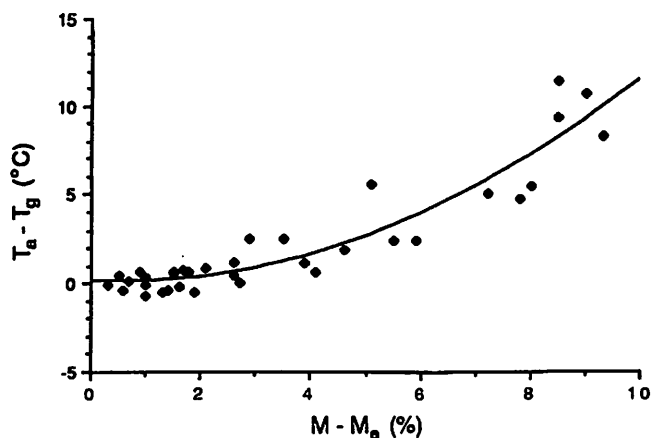


Fig. 10. The difference between drying air temperature, T_a , and average temperature measured at each layer, T_g , versus the difference between average moisture content of each layer, M , and equilibrium moisture content of wheat, M_e .

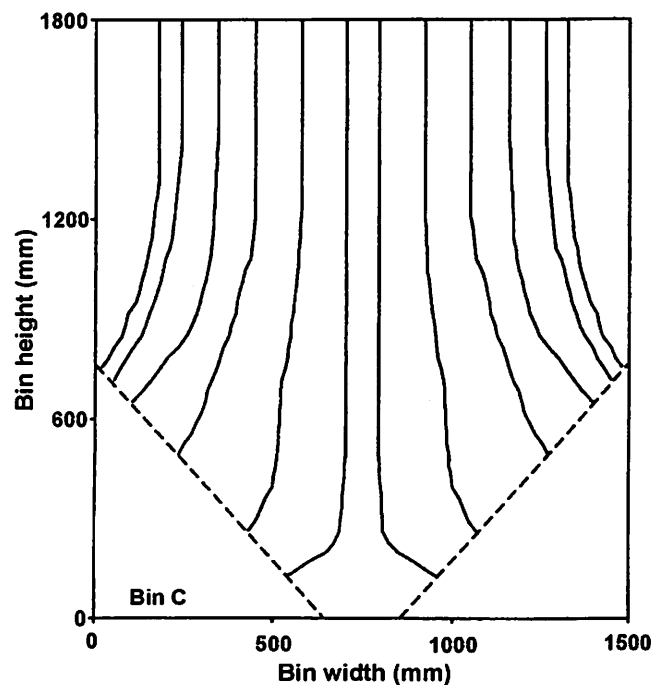
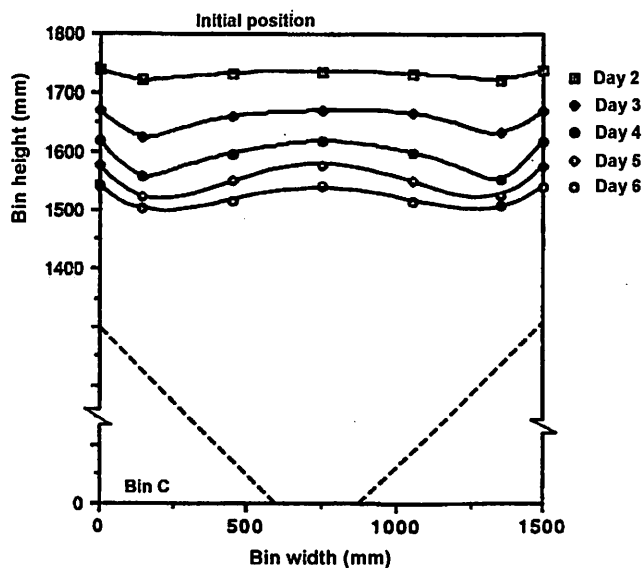
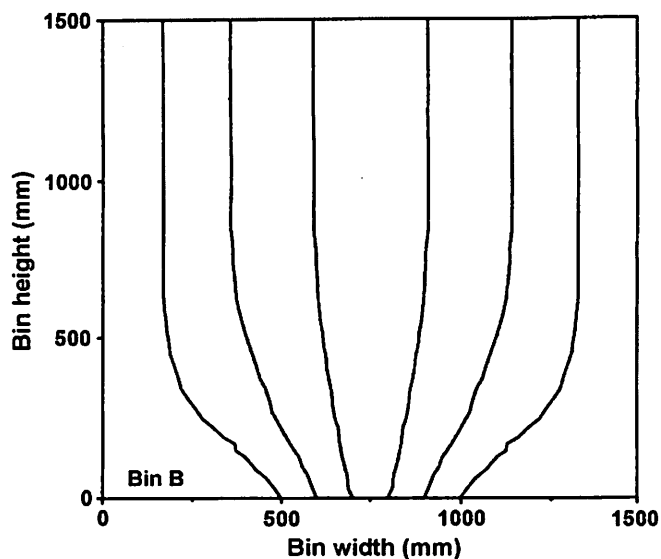
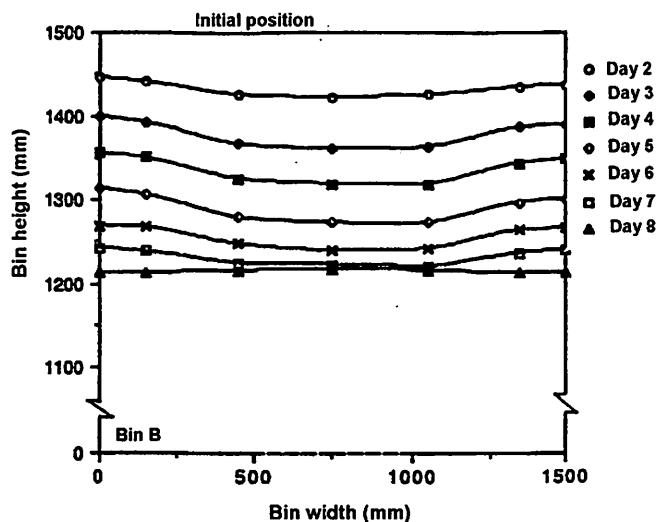


Fig. 11. Top surface profiles of the grain bed during the drying test in the bin with floor B (initial average m.c. 22.5%, final average m.c. 10.6%) and with floor C (initial average m.c. 22.9% and final average m.c. 12.0%).

Fig. 12. Calculated airflow streamlines in the bin with floors B and C.

between the temperature of the drying air in the plenum, T_a , and the average temperature of each layer, T_g , against the difference between the average moisture content of grain of each layer, M , and the equilibrium moisture content of the grain, M_e . M_e was calculated using the equation for wheat from ASAE Data D245.4 (ASAE 1994c).

The relationship between the temperature difference ΔT and the moisture content difference ΔM was represented by a polynomial of second degree ($R^2 = 0.88$):

$$\Delta T = 0.117 - 0.1243\Delta M + 0.1268\Delta M^2$$

where:

$$\Delta T = T_a - T_g \text{ (}^\circ\text{C)}, \text{ and}$$

$$\Delta M = M - M_e \text{ (\% w.b.).}$$

This is the equation that was used to monitor and control all the tests in the experimental study.

Shrinkage

As drying progressed, the top surface of the grain bed dropped. In the bin with floor A, the top surface was approximately horizontal during the entire drying time. The surface dropped from 1450 mm to about 1160 mm with total volumetric shrinkage of about 20% when the grain was dried from 21% to an average of about 10%. Figure 11 shows the locations of the top surface of the drying beds in the bin with floors B and C

Table III. Daily record of the static pressure in plenum and the supply airflow rate during drying tests in the bin with floors A, B, and C.

Day of drying	Floor A		Floor B		Floor C	
	Airflow rate (m ³ /s)	Static pressure (Pa)	Airflow rate (m ³ /s)	Static pressure (Pa)	Airflow rate (m ³ /s)	Static pressure (Pa)
1	0.056	299.9	0.045	298.1	0.074	299.5
2	0.058	299.9	0.046	299.5	0.075	299.9
3	0.057	299.5	0.044	300.2	0.072	300.2
4	0.054	298.8	0.042	299.9	0.067	299.5
5	0.052	298.1	0.041	300.9	0.066	299.9
6	0.050	298.8	0.041	299.9	0.064	299.5
7			0.040	299.5		
8			0.040	298.8		

during drying. The profiles of the top grain surface changed from horizontal to curved because of the uneven shrinkage. A greater shrinkage occurred at the locations where the grain was drier. However, compared to the total depth, the variation of the grain depths due to the curved top surface was still relatively small. The top surface tended to become horizontal at the end of a drying test, except in bin C where the top surface remained uneven throughout the drying.

Airflow effect

The non-uniform drying of grain in the bin with floors B or C was due to the airflow distribution in the two bins not being uniform. Figure 12 shows the simulated airflow stream lines for floors B and C. The simulation procedure was outlined in Gu (1994). The non-uniformity of airflow with floors B and C was in the area near the air entrance. In locations away from the air entrance, the airflow tended to become parallel. The non-uniformity of airflow in the bottom part of the bins established the curved drying front.

The actual volume of drying air received by the grain varied from bin to bin. Table III lists the daily records of the plenum static pressure and the airflow rates supplied to the bin with each of the floors. The data show that although the static pressure in the plenum was almost constant, at 300 Pa for each of the floors, the air supplied to the bin with floor C was the largest (0.070 m³/s) and to the bin with floor B was the smallest (0.043 m³/s). Air supplied to the bin with floor A was 0.055 m³/s.

The difference in the perforated floor area affected the amount of air supplied to the bin with each floor. Taking the ratio of the perforated area of floor A to the cross sectional area of the experimental bin as 1, this ratio was 0.33 for floor B, and 1.35 for floor C. The smaller perforated floor area of floor B resulted in extra resistance to airflow so the pressure was reduced and the quantity of air entering the bin was reduced. This fact was supported by the measurement of static pressures across the bottom layer of grain in a thickness of 200 mm on the perforated floor. For the bin with floor A, the pressure drop was

35 Pa, with floor C 36 Pa, and with floor B 76 Pa (Gu et al. 1996). For the bin with floor C, the larger perforated floor area and continuously decreasing grain bed depth along the slanted floor from the centre to the sides of the bin allowed more air to enter the grain bed at the same plenum pressure.

A slight increase in airflow on the second day of drying was noticed (Table III). This increase was attributed to a temporary increase in the bulk porosity of the grain due to grain kernel shrinkage. After the second day, the airflow rate supplied to each bin decreased slightly as drying progressed. This decrease was due to grain consolidation resulting from grain movement because of further grain shrinkage. The supply airflow rate at the end of the test was 12% lower than that at the beginning of the test in the bin with floor A, 15% lower with floor B, and 13% lower with floor C.

CONCLUSIONS

Although these experiments were conducted in a model rectangular bin, the results can be generalized or used as a reference for larger rectangular or circular bins. For example, the results from the bin with floor B can be used as reference for circular bins with partially perforated floor, or for rectangular bins with similar flooring. The bin with floor C, on the other hand, can be considered as a simplified model of hopper bottom bins. Similar moisture or temperature distributions as those resulting from the experimental study should be observed within these types of bins.

Conclusions from the study are:

1. When grain was dried in the bin with centrally perforated floor (Floor B), moisture contents of the grain were distributed unevenly throughout the bin with higher moisture contents at the sides of the bin than that at the centre.
2. When grain was dried in the bin with the slanted perforated floor (Floor C), grain at the centre of the bin remained near the initial moisture content of 20% when the average moisture content of the bin was 14%. Grain on the sides of the bin had to be over-dried to dry the grain at the centre of the bin.
3. For ambient air in-bin drying, inter-granular air temperature contours and moisture content contours in a drying bed had similar profiles. Higher temperatures corresponded to lower moisture contents and vice versa. Progress of ambient air in-bin grain drying can be monitored by the measurement of inter-granular air temperature.
4. For ambient air in-bin drying of wheat, inter-granular air temperature within the grain mass remained at or near the wet-bulb temperature of the drying air until the grain moisture content decreased to 15%.
5. Grain dried in the bin with non-uniform airflow resulted in a curved grain surface due to uneven bulk shrinkage. Wheat shrinkage was about 20% (on volume basis) when the moisture content of the grain was reduced from 21 to 10%.
6. At the same plenum static pressure and with the same volume of grain, less air entered the bin with partially perforated floor (Floor B) compared to the bin with fully perforated floor (Floor A) or slanted perforated floor (Floor C).

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