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DRYING CHARACTERISTICS OF THIN-LAYERS OF WHEAT AND BARLEY AT NEAR-AMBIENT TEMPERATURE

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ABSTRACT

Thin-layers of wheat and barley are dried at near-ambient temperatures (3.5°C - 50°C) in order to obtain the intrinsic drying data. The well established apparatus was modified to enable it to record all the sample weight data in still air by using a purpose-built automatically controlled sliding valve. The air could be diverted in less than 0.5 seconds and a 7 second period was required to attain a steady weight reading. With this apparatus, very smooth drying curves were obtained. The data of sample weight, drying temperature and dew point temperature were recorded continuously. The drying process was terminated when the moisture content change in 24 hours was less than 0.004 d.b. This was achieved by drying a sample for about a week. The final points were recorded as the dynamic equilibrium moisture content (EMC).

The drying data were then fitted to the exponential Newton model and the dynamic EMC data were fitted to the Modified-Chung-Pfost model. All the fitted parameters are given and comparison is made with previous published data. The comparisons show that the current drying constants are lower than the previous data, the dynamic EMC data obtained for wheat and barley agree with the previous data. The results show that to obtain the drying constant in the exponential Newton model, adequate drying time is necessary.

Key Words: Barley, Drying constant, Equilibrium moisture content, Isotherm equation, Low temperature, Thin-layer drying, Wheat

INTRODUCTION

Thin-layer drying is a technique to obtain the intrinsic drying characteristics of a material. With this drying information, a deep bed of grain can be divided into a finite number of thin-layers and a simulation model can be established. In these divided thin-layers, the amount of the moisture removed or adsorbed by the grain is determined by the thin-layer drying equation applicable in the range of air conditions. Many deep bed simulation models have been developed to predict the drying of grain. Therefore a more accurate measurement of the thin-layer drying of grain is very important to the simulation models for predicting the deep bed drying well.

Drying/cooling is a current strategy being developed for the operation of grain stores. This can be achieved by low temperature ambient drying and cooling during storage or by high temperature drying followed by cooling in storage. The combination of drying and cooling lowers both the water activity and temperature of grain. This will minimize the biological activity of both the grain and potential pests and hence enable long-term storage whilst reducing the use of pesticides. Unfortunately, there is little data on low temperature moisture transfer for wheat and barley available.

The thin-layer drying of wheat and barley can be traced back to 1950s - 1960s (Simmonds *et al.*, 1953; Boyce, 1965). These drying data are still used today. However the lack of accurate measurement techniques and methods at that time results in some doubt as to the accuracy of these data. Therefore it is useful to carry out the thin-layer drying of wheat and barley with more recent technology.

The purpose of the current work is to obtain complete drying curves during low temperature drying for a better understanding of the intrinsic drying characteristics of wheat and barley at near-ambient temperature.

THIN-LAYER DRYING EQUATIONS

As early as in the 1920s, Lewis (1921) suggested that during drying of porous hygroscopic materials, the drying rate is proportional to the difference between the instantaneous moisture content and its equilibrium value at the same drying conditions. This expression is analogous to Newton's law of cooling:

$$\frac{dM}{dt}=-K(M-M_e) \qquad (1)$$

where K is drying constant (min^{-1}), t is drying time (min). The integration of Eqn (1) yields:

$$\frac{M-M_e}{M_0-M_e}=\exp(-K*t) \qquad (2)$$

where M_0 and M_e are the initial and equilibrium moisture contents (decimal d.b.) respectively. Actually this equation is the first item of the analytic series solution of the diffusion equation. Therefore the equation has a strong theoretical basis. The limitation of Eqn (1) is that the equation implies that all the resistance to drying is at the surface of the kernel. However because of its simplicity and high computational speed, almost all the investigators apply it to the thin-layer drying of wheat and barley (Henderson and Pabis, 1961; O'Callaghan *et al.*, 1971; Jayas and Sokhansanj, 1986; Boyce, 1965; Bruce, 1985; Jayas and Sokhansanj, 1989).

The drying constant K in Eqn (1) is usually correlated with drying air temperature T (°C) by the Arrhenius relationship as follows:

$$K=a*\exp\left(-\frac{b}{T+273.15}\right) \tag{3}$$

M_e in Eqn (1) is closely related to the drying air relative humidity, RH and temperature, T. There are many models developed to express the relationship between them. The most commonly used is the Modified-Chung-Pfost equation which was developed as follows and fitted to the data of wheat and barley (Pfost *et al.*, 1976):

$$RH=\exp\left[-\frac{C1}{T+C2}*\exp(-C3*M_e)\right] \tag{4}$$

EXPERIMENTAL

Materials

The wheat sample was of the variety Riband, a winter wheat. It was grown in the north east of England in the 1992 season. It was obtained at a moisture content of 29% d.b. and did not require rewetting for the experiments. It was stored in a refrigerator before testing.

The barley sample was of the variety Camargue, a spring barley. It was grown in the south east of Scotland in the 1991 season. It was floor dried at room temperature to around 16% d.b. and stored in a refrigerator. The barley samples were rewetted to a moisture content of 28% d.b. for the experiments. The rewetting was carried out by rotating the conditioning barrel containing the integral mixing of water and barley over a 48 hour period. The rewetted samples were sealed into double layer plastic bags and stored in a refrigerator for one week so as to let the samples reach their equilibrium state within the kernels and outside.

Apparatus

The apparatus consists mainly of an ice bank, a saturating column, a thin-layer drying unit and a data logging system. The ambient air is delivered upward to the saturating column and saturated with water pumped from the ice bank, via a buffer tank at a controlled temperature, downward from the top of the column which is packed with plastic rings. The saturated air exits from the top of the column and is heated by air heaters to the desired temperature. It then flows upward through the thin-layer drying unit. A circular drying tray containing a wheat or barley sample inside the drying unit is supported by a collar suspended by a frame from a digital balance. The signals of weight and temperature from the balance and thermalcouples respectively are recorded by a microcomputer running the data logging software. With this apparatus, the air flow rate can be adjusted between 0 to 0.1 m^3/s. At the maximum air flow rate, the maximum air temperature achievable is 75°C and the maximum dew point is 35°C. The lowest air temperature and air dew point attained were 3.5°C and 1.2°C, respectively.

A recent modification to the apparatus was to add an automatic solenoid-controlled sliding valve for the diversion of drying air for weighing the sample in still air. The air can be diverted in less than 0.5 seconds and a 7 second period was required to get a steady reading from the balance in still air. The data logging interval can be adjusted from 5 min to 1 hour. The air-off period for data recording can be set between 5 to 30 seconds.

Measurement

The moisture content was determined by using the American Society of Agricultural Engineers Standard ASAE S352.2. This standard uses a 10 g sample of whole wheat and barley grains oven dried for 19 and 20 hours respectively at an oven temperature of 130°C. All the samples were weighed to 0.0001 g. Five replicate samples were measured and the mean value was taken.

The continuous changing of the moisture content of a sample was calculated using the recorded data of weight of the sample weighed in still air during the drying process. The balance used for weighing had a capacity of 5,500 g with a sensitivity of 0.01 g.

The dry-bulb temperature of the drying air was measured using copper/constantan thermocouples with an accuracy of ± 0.15°C. Two-sets of three thermocouples, located directly above and below the drying tray respectively, measured the exit and inlet temperatures of the tray. The dry-bulb temperature was the mean value of these six points.

The air humidity was calculated by measuring the temperature of the air leaving the saturation column and assuming the air saturated. Saturation was checked by means of a differential psychrometer which had a sensitivity of 0.005°C. The air was above 99% saturated.

Procedure

A sample of approximately 350 g was evenly spread on the drying tray to form a single layer. When the apparatus was stable at the required drying condition, the air was diverted in order to insert the tray into the drying chamber in still air. Immediately after the balance reading was stable, the initial weight was recorded and the drying air flowing upwards through the sample commenced. At the same time, a sample was taken from the same storage bag to determine the initial moisture content. The data were recorded every 15 min until the 24 hour change of moisture content was less than 0.004 d.b. Normally such an experiment would last from 5 to 7 days. After the experiment was terminated, a sample was taken from the dried sample to determine its final moisture content. The others were sealed into a small plastic double layer bag and kept in a freezer for future use if necessary.

RESULTS AND DISCUSSION

The experimental plan for thin-layer drying of wheat and barley is tabulated in Table 1. To complete this plan, about eight months were required. The temperatures are largely in the lower ambient range although some higher temperatures are included for comparison with previous work.

Fig. 1 shows the example of the drying curves of wheat. Similar drying curves for barley were obtained. Each curve in Fig. 1 consists of about 600 experimental points. Since all the data were recorded in still air, this eliminated the effect of moving drying air on weighing and hence reduced the error of sample weighing to only the error of the balance. Therefore very smooth curves are observed. Fig. 1. also indicates that the moisture content of a sample decreases quickly in the first several hours of drying, but the moisture content change is still considerable even after 24 hours of drying especially at high temperatures. It is therefore clear that to get the intrinsic drying rate, it is necessary to consider an extended drying period.

If the drying data in Fig. 1 are fitted to Eqn (2), the drying constant for each curve can be obtained. By and large, there are two methods of finding the drying constant. One is to apply Eqn (2) with the known M_e value. In this case, the M_e value should be a reasonable approximation to reduce fitting error. Another method is to use the following equation for fitting:

$$M=(M_0-M_e')*\exp(-K*t)+M_e' \qquad (5)$$

where M_e' is the fitted equilibrium moisture content (d.b.). In this case, every fitting will result in two fitted parameters K and M_e'. However the fitting error will be smaller than using Eqn (2). This method is currently employed. A NAG (Numerical Algorithms Group 1990) Fortran library routine E04FDF was used to regress nonlinearly the drying data. E04FDF routine is used to find the value of K and M_e' with which Eqn (5) will give the minimum of the residual sum of squares of M. Every individual fitted value of drying constant is collected and fitted to Eqn (3) to find its relationship with drying temperature. Table 2 lists the current results and the results of the previous studies.

Figs 2 and 3 show the comparison of the current results with the previous studies for wheat and barley, respectively. It is observed that with the increase of drying temperature, the drying constant increases. Figs. 2 and 3 also show that the present drying constants are lower than the others. This is because a much longer drying time was used in the experiments. Since Fig. 1 shows that short drying time is inadequate in getting a complete drying curve, it seems that the previously published data overestimate the drying rate that would be observed in the slow drying experienced at lower temperatures.

After each run of the experiment was finished, the sample was used to determine the final moisture content by the oven method. This value is considered as equilibrium moisture content M_e. The M_e value was compared to the value of the final point of each curve and a very good coincidence between them is noticed. This also verifies the accuracy of the drying data. A comparison of M_e' and M_e showed that both data agree well. Therefore the oven determined M_e is used as equilibrium moisture content which should be considered as dynamic equilibrium moisture content.

For fitting M_e data, The E04FDF routine was applied again. The fitted equations are as follows:

For wheat

$$RH=\exp\left[-\frac{662.69}{T+67.981}*\exp(-0.15681*M_e)\right] \tag{6}$$

and for barley

$$RH=\exp\left[-\frac{414.42}{T+30.275}*\exp(-0.17020*M_e)\right] \tag{7}$$

In Eqns (6) and (7), RH is in decimal while M_e is in percentage dry basis.

The comparison of the Eqns (6) and (7) with the published data were made. The comparison showed that the current curves lie above but close to the other curves predicted by the published data. This is because the drying time is not long enough to let the wheat and barley samples reach their equilibrium state with the drying air. In the experiment at low temperature (about 5°C) the constant weight of the sample was observed for 24 hours and in the experiment at high temperature ($\geq$40°C), when the experiment was terminated, a slight change of the sample weight was still observed as shown in Fig. 1. Nevertheless, it is well understood that the dynamic EMC is higher than the EMC.

CONCLUSIONS

1. The existing apparatus for thin-layer drying/cooling was modified. This enabled the recording of the drying data in still air. Using this apparatus, very smooth drying curves were obtained.
2. The thin-layer drying curves for wheat and barley were obtained for a range of temperatures and humidities, largely in the lower ambient range.
3. The drying constant in the exponential Newton model is determined and

found to be lower than that of previous workers due to the longer drying times employed in these experiments. These values may be more appropriate to the low rate drying/cooling processes taking place under ambient storage conditions.

4. A set of dynamic equilibrium moisture content data corresponding to the drying rate data were also obtained and found to be close to, but higher than, the published data on static equilibrium moisture content as would be expected.

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Table 1. List of the experimental conditions.

Wheat			Barley		
Air Temp. (°C)	Dew Point (°C)	M_0 (d.b.)	Air Temp. (°C)	Dew Point (°C)	M_0 (d.b.)
3.5	1.6	0.29456	3.9	1.3	0.27984
3.9	1.4	0.29480	6.6	2.5	0.25367
5.0	2.7	0.28844	7.9	2.5	0.25751
7.0	3.2	0.28705	7.9	4.1	0.26787
7.9	2.6	0.28702	11.8	4.3	0.26746
10.8	2.7	0.28911	11.8	8.5	0.25469
10.8	6.8	0.28962	15.7	5.1	0.26990
14.6	2.6	0.28876	19.5	4.8	0.25902
18.4	2.7	0.28564	19.5	10.1	0.26154
18.4	13.6	0.29555	19.5	13.9	0.26002
18.4	16.3	0.28861	19.5	17.2	0.27391
19.5	9.2	0.29371	19.6	4.4	0.26541
23.4	2.6	0.28821	24.5	4.4	0.26542
30.4	2.7	0.28816	29.5	4.5	0.26472
40.2	2.7	0.28811	39.3	4.4	0.26894
49.7	2.9	0.29279	49.2	4.5	0.25074

Table 2. Comparison of the drying constants of wheat and barley.

	Author	Temp. (°C)	Drying constants	
			a	b
Wheat	Henderson & Pabis (1961)	21 - 76.5	1.667×10^{-5}	5202.2
	O'Callaghan *et al.* (1971)	26.7 - 76.5	1.2×10^{5}	5094
	Jayas & Sokhansanj (1986)*	5 - 35	1.791×10^{-3}	6.06×10^{-6}
	This work	3.5 - 49.7	635.13	3766.3
Barley	Boyce (1965)	37.8 - 71.1	8358.0	4426.1
	Bruce (1985)	50 - 150	234.0	3086.0
	Jayas & Sokhansanj (1989)*	5 - 35	1.238×10^{-3}	4.28×10^{-6}
	This work	3.9 - 49.2	84.944	3258.3

* The drying constant equation is $K = a + b\,T^2$.

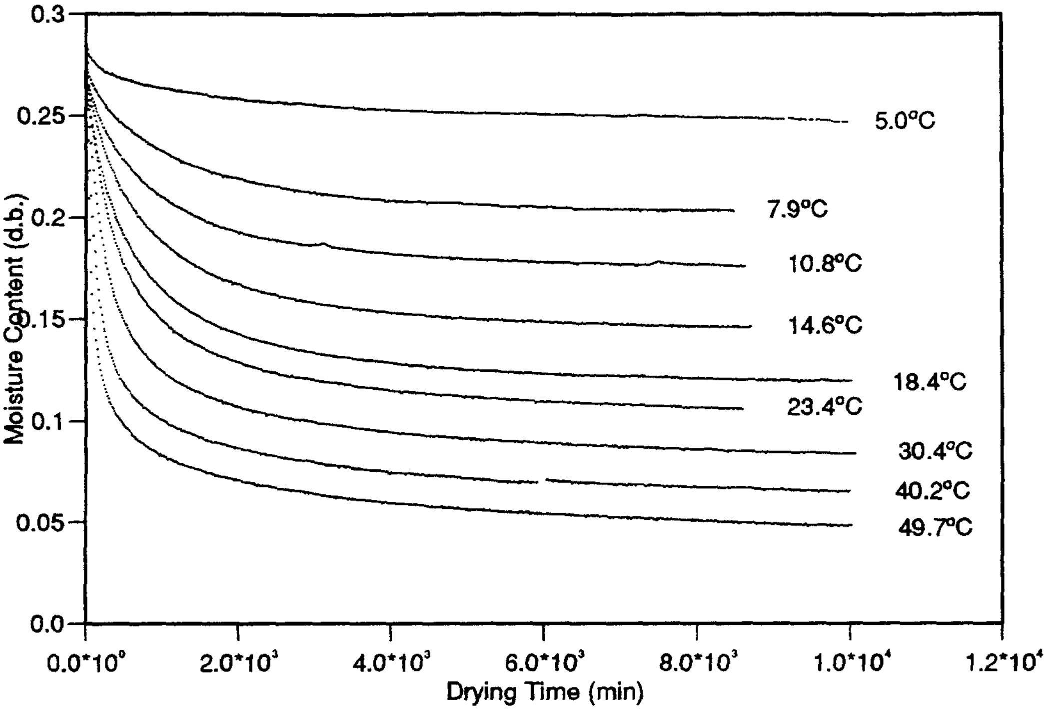

Fig. 1. The drying curves of wheat at various temperatures.

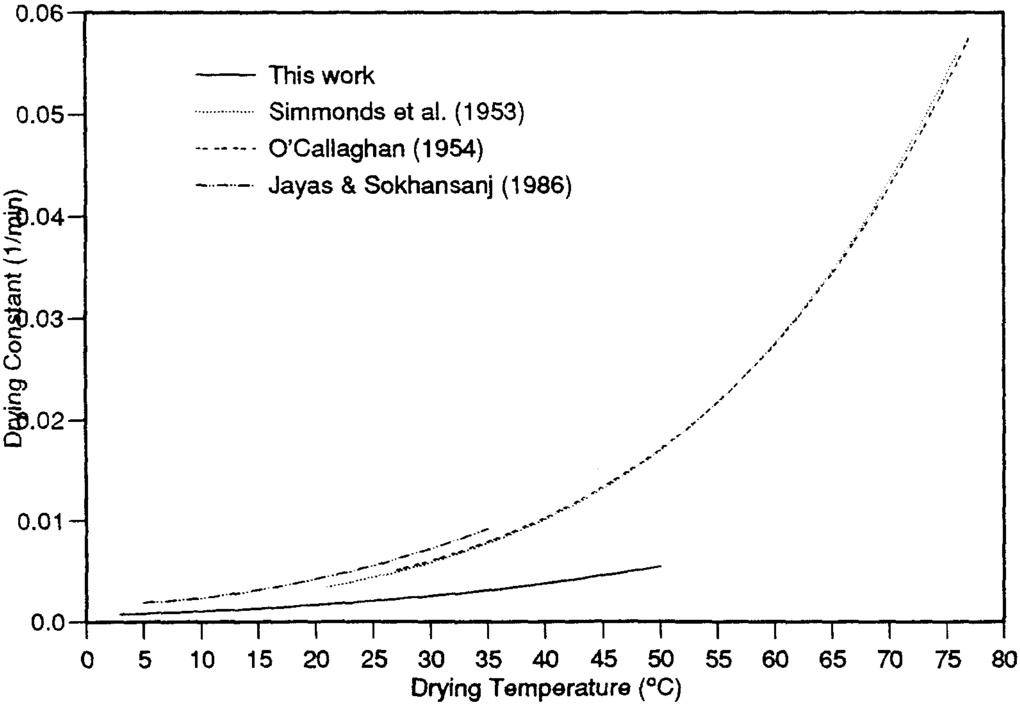

Fig. 2. The comparison of different drying constants for wheat.

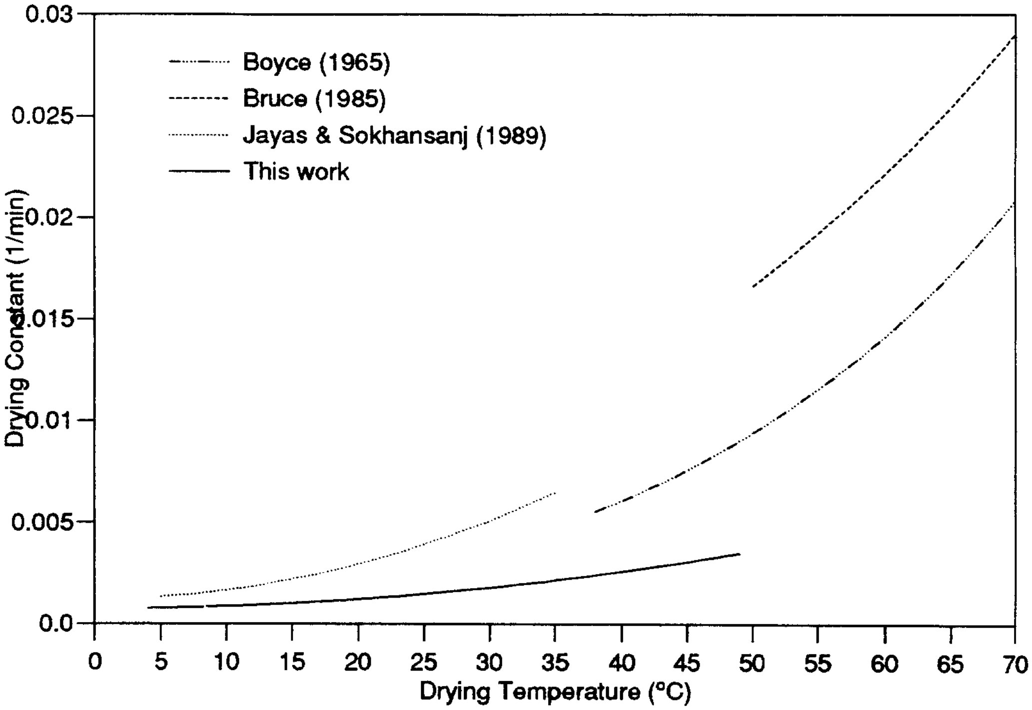

Fig. 3. The comparison of different drying constants for barley.