

Thin-layer drying of barley at low temperatures

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Jayas, D. S. and Sokhansanj, S. 1989. **Thin-layer drying of barley at low temperatures.** *Can. Agric. Eng.* **31**: 21–23. Thin-layer drying characteristics of barley were determined at temperatures ranging from 5 to 35°C and relative humidities ranging from 35 to 80% for two airflow rates (0.3 m³/(s•m²) and 0.6 m³/(s•m²)) and an initial moisture content of 16.5% (wet mass basis). Temperature had the most significant effect, airflow rate had no effect and air relative humidity had very little effect on drying characteristics of barley.

INTRODUCTION

Barley is one of the major crops grown in Canada. During the period from 1980 to 1984, an average of 10 Mt of barley were produced and stored annually in Canada (Anonymous 1984). A significant portion of this barley is dried and aerated on farms. The present trend in the agricultural industry is to dry grain with near-ambient temperature air. Many deep bed simulation models have been developed to predict near-ambient drying of barley and other crops. A comprehensive review of simulation models on near-ambient drying has been reported by Sharp (1982). The reported simulation models are either equilibrium models or thin-layer models. The basic assumption under equilibrium models is that air leaves the grain in equilibrium with the moisture in the grain at all times, although this may not necessarily be true. In thin-layer models (Henderson and Henderson 1968), a deep bed of grain is divided into a finite number of thin layers. Depending on the air conditions in the vicinity of the thin layer, the amount of moisture removed or absorbed by the grain is determined by a thin-layer drying equation applicable in the range of air conditions. The thin-layer models usually predict drying of deep beds more accurately.

Singh and Sokhansanj (1984) observed that there is little information on thin-layer drying of barley at temperatures and relative humidities encountered during a normal drying season in Canada. The present study was undertaken to determine the thin-layer drying characteristics of 16.5% initial moisture content barley at combinations of temperatures ranging from 5 to 35°C and relative humidities ranging from 35 to 80% for two levels of airflows (0.3 m³/(s•m²) and 0.6 m³/(s•m²)).

THIN-LAYER DRYING EQUATION

The most commonly used equation to describe the thin-layer drying of cereals is that of Page (1949):

$$MR = \exp(-Kt) \quad (1)$$

where:

- MR = moisture ratio $(M - Me)/(Mi - Me)$;
- M = moisture of grain at any time, dry basis (DB);
- Mi = initial moisture of grain (DB);
- Me = equilibrium moisture of grain (DB);
- t = time (min); and
- K = drying constant (min⁻¹).

Other investigators (Lewis 1921; Newman 1932a, 1932b) have used this equation to describe drying of porous materials other than cereals.

We have used this drying equation to describe the thin-layer drying characteristics of barley. The drying constants K for each test were determined by fitting Eq. 1 to experimental data using the general linear models (GLM) and nonlinear regression (NLIN) procedures of Statistical Analysis Systems Institute Inc. (SAS 1985).

MATERIALS AND METHOD

Drying apparatus

The thin-layer drying apparatus is shown schematically in Fig. 1. The plenum and drying duct were made of 10-mm-thick plywood and lined with aluminum foil on the inside. The duct was fitted with a honeycomb (20-mm × 20-mm apertures) to straighten the airflow. An access door (200 mm wide) was cut in the top surface of the duct and was closed during experiments using a hinged door. A hole of 65-mm diameter was drilled in the bottom face of the duct at midspan. The stem of the sample holder was passed through the hole so it would rest upon the platform of a weighing scale. To minimize the effect of moving air on the weighing scale, this hole was covered with an aluminum plate around the stem of the sample holder. To force air through the sample a wooden piece with a U-groove (30 mm wide and 20 mm deep) cut in it was attached to the sides of the drying duct.

Four electric resistance heaters each with a capacity of 750 W were incorporated in the plenum to heat the air for the hot-air drying experiments. Since this study was conducted at low temperatures, the electric heaters were not turned on. For these experiments the air was conditioned to the desired temperature and relative humidity using an air conditioning unit (Aminco Aire, Parameter Generation and Control Inc., 1104 U.S. 70 West, Black Mountain, NC 28711). The dry bulb and wet bulb temperatures of the drying air were monitored at 50 mm upstream of the sample holder to assure constant drying conditions. The temperatures were measured using type T (copper-constantan) thermocouples and were recorded using a Fluke data logger. For wet bulb temperature, the thermocouple junction was wrapped in a wet wick extending from a water-filled bottle. The relative humidity of the drying air was calculated from dry bulb and wet bulb temperatures measured within 0.5°C. The weighing scale had a resolution of 0.01 g. The sample holder was made of two detachable square frames with brass screens.

Drying run

The air conditioning unit was started 1 d prior to data collection to attain stable air temperature and relative humidity. A layer of barley one kernel thick was spread over one of the brass screens of the sample holder and was covered with the other

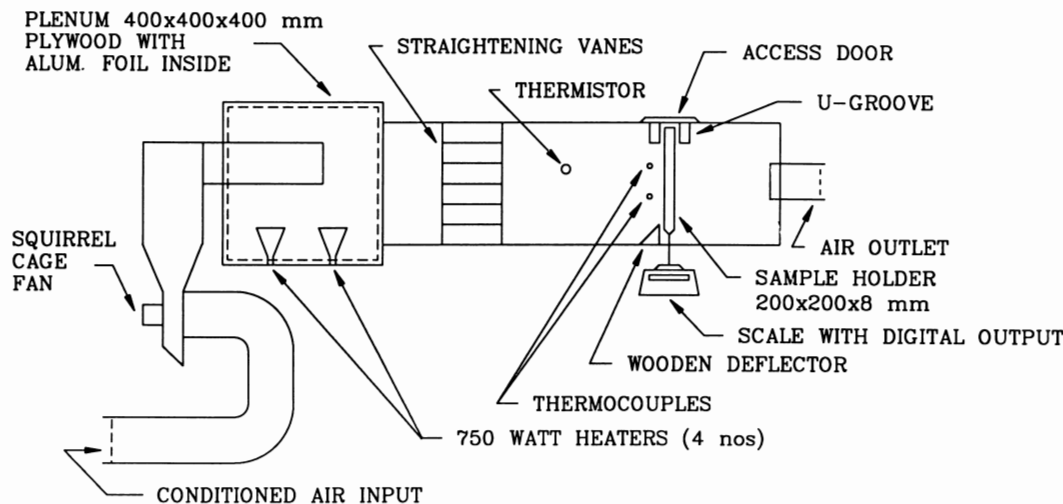


Fig. 1. Schematic of the experimental thin-layer dryer.

screen. The screens were clamped together with heavy paper clips. The data acquisition program was activated. The sample holder was then passed through the bottom hole of the duct to rest on the platform of the weighing scale. The sample was at a right-angle to the direction of airflow. After assuring the sample holder was free on all sides, a computer program was started to record the mass loss of the sample every 2 s for 2 h. This duration was selected for two reasons. First, in most of the simulation models the time interval chosen is usually from 1 to 2 h. Second, environmental data used in simulation models are collected on an hourly basis and therefore change the air conditions in the vicinity of the thin-layer at each hour. Also it is not common to find more than 2 h of constant atmospheric air conditions. The drying constants at the set air conditions were determined by fitting data to Page's model (Eq. 1).

Samples

The samples of barley (*Hordeum vulgare* L. cv. 'Klages') were obtained from a farm near Saskatoon at an initial moisture content of about 18%. The samples were dried at room temperature to 17.0% and were then stored in plastic bags in a freezer maintained at -10°C . Hustrulid (1962, 1963) compared the drying rates of naturally moist, frozen and remoistened corn and wheat and reported that the freezing of samples did not change the drying characteristics. Two days prior to an individual test, a sample was transferred to a refrigerator for thawing and left for at least 12 h at room temperature for temperature equilibration. The actual initial moisture content of each sample was determined prior to each test for determining the dry matter content.

Moisture measurement

Moisture contents of barley samples were determined by using the American Society of Agricultural Engineers Standard ASAE S352.1. Triplicate samples of barley were dried at 130°C for 20 h in an air convection oven and moisture contents were calculated on wet and dry basis (ASAE 1985).

Airflow measurement

The velocity of air at nine points in a cross section of the duct was measured using a hot wire anemometer. These measurements were done at two locations, 50 mm upstream and

downstream of the sample holder while it was filled with barley. Two levels of average airflow $0.3 \text{ m}^3/(\text{s}\cdot\text{m}^2)$ and $0.6 \text{ m}^3/(\text{s}\cdot\text{m}^2)$ were used.

Equilibrium moisture content

Equilibrium moisture content of the barley at particular combinations of temperature and relative humidity were determined using the modified Henderson and Chung-Pfost equations given in ASAE Data D245.4 (ASAE 1985). Calculated values from the two equations were not exactly the same but were very close, therefore they were averaged to find the mean equilibrium moisture content.

EXPERIMENTAL DESIGN

Drying characteristics of barley were determined at five temperatures 5, 12.5, 20, 27.5 and 35°C ; at four relative humidities 35, 50, 65 and 80%; at one initial moisture content 16.5% wet mass basis; and at two airflow rates $0.3 \text{ m}^3/(\text{s}\cdot\text{m}^2)$ and $0.6 \text{ m}^3/(\text{s}\cdot\text{m}^2)$. Due to limitations imposed by the air conditioning unit, all four levels of relative humidities could not be used at all temperatures. The combinations of temperature and relative humidity used are given in Table I. Three replicates were run at each condition.

The temperatures and relative humidities are typical of a normal drying season and the initial moisture content of 16.5% is based on the assumption that barley usually harvested in the moisture content range of 15.5–17.5% can be dried successfully using near-ambient temperature during a normal drying season.

RESULTS AND DISCUSSION

Effect of airflow rate

The measured moisture ratios for the three replicates varied within 5%. The maximum deviation in drying constants based on three replicates for any given condition was 10.4% (Table I). The difference in K values using the GLM and NLIN procedures was insignificant ($P < 0.05$). The values of K obtained using GLM procedure are reported in this paper.

The drying constants were not significantly different ($P < 0.05$) for the two airflow rates. The values for airflow rate of $0.3 \text{ m}^3/(\text{s}\cdot\text{m}^2)$ were within 3% of the values given for airflow rate of $0.6 \text{ m}^3/(\text{s}\cdot\text{m}^2)$. Li and Morey (1984) also noticed

Table I. Drying constants for barley at various air conditions†

Air condition		Drying constant <i>K</i>	
Temp‡ (°C)	RH§ (%)	Mean¶ (min ⁻¹)	SD (min ⁻¹)
5.0	80	0.00149	0.00012
12.5	80	0.00171	0.00017
20.0	80	0.00267	0.00016
27.5	80	0.00410	0.00018
35.0	80	0.00591	0.00031
12.5	65	0.00178	0.00018
20.0	65	0.00278	0.00029
27.5	65	0.00468	0.00028
35.0	65	0.00672	0.00032
20.0	50	0.00294	0.00021
27.5	50	0.00510	0.00043
35.0	50	0.00588	0.00032
27.5	35	0.00521	0.00027
35.0	35	0.00688	0.00041

†Airflow rate was 0.6 m³/(s·m²).

‡Temperature varied ±1°C.

§Relative humidity varied ±3%.

¶Sample size 3.

almost no effect on the drying rate of corn at 49 and 93°C for three airflow rates 0.1, 0.3 and 0.5 m³/(s·m²). It is hypothesized that airflow might affect the drying rate when using very low airflows but these two studies were not conducted at low airflows.

Effect of relative humidity

In general, as relative humidity increased at constant temperature and airflow rate, drying was slowed. But the effect was not very significant. Li and Morey (1984) studied the effect of relative humidity on drying of corn. Their graphical representation of moisture ratio and drying time at 49°C (air temperature) shows that 40% RH resulted in a higher moisture removal than the 5% RH. Crank (1956) stated that it would be difficult to prove mathematically that dehydration into low humidity atmosphere could be higher than that into a perfectly dry atmosphere. He mentioned that one explanation for this could be the formation of a hard skin (case hardening) through which the escape of further moisture would be slow. We also noticed this phenomena at one temperature. At 35°C, drying is faster for 65 and 80% relative humidity compared to 50% relative humidity, when mean values of drying constants are considered (Table I). However, they are not statistically different for $P < 0.01$ but are statistically different for $P < 0.05$.

Effect of temperature

Temperature had the most significant effect on the drying rate of barley. The drying constant increased parabolically with increasing temperature. The best-fit equation relating the drying constant to temperature was:

$$K = 0.001238 + 4.28 \times 10^{-6} \times T^2 \quad (2)$$

where:

K = drying constant (min⁻¹) and

T = drying air temperature (°C).

The correlation coefficient for this equation was 0.95. If relative humidity is also incorporated into the analysis K is related to temperature and relative humidity as follows:

$$K = 0.002541 + 4.0130 \times 10^{-6} \times T^2 - 1.78447 \times 10^{-5} \times RH \quad (3)$$

where RH is relative humidity (%).

The correlation coefficient for this equation was 0.97. The minor increase in correlation coefficient from 0.95 to 0.97 indicates that the relative humidity had very little effect on the drying constants. Hence, it is suggested that Eq. 2 can be used to find drying constants for temperatures in the range 5–35°C. As an example, the predicted values of moisture ratios with K calculated from Eq. 2 were within 4% of the measured moisture ratios at 27.5°C and 50% relative humidity. The estimated drying constants can be used in the simulation models developed to predict deep bed drying of barley. Henderson and Henderson (1968) have reported a method for using the thin-layer drying equations in simulation of deep bed drying of cereals.

CONCLUSIONS

From the results of this study, it is concluded that the temperature (5–35°C) had the most significant effect, airflow rate in the range of 0.3–0.6 m³/(s·m²) had no effect and relative humidity of the air (35–80%) had very little effect on the drying constants of barley.

ACKNOWLEDGMENTS

We thank Miss Banafsheh Sokhansanj for her help in data collection.

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