Drying of rewetted wheat spikes

P. A. VERSAVEL and W. E. MUIR

Department of Agricultural Engineering, University of Manitoba, Winnipeg, Manitoba R3T 2N2. *Received 8 January 1987, accepted 5 August 1987.*

Versavel, P. A. and Muir, W. E. 1988. **Drying of rewetted wheat spikes**. Can. Agric. Eng. **30**: 57–60. Drying constants of rewetted spikes of hard red spring wheat (cv. Neepawa) were determined using three initial moisture contents, three temperatures, three relative humidities and two thermal radiation levels. The effects of changing conditions on the drying constant were evaluated. Drying constants were determined using nonlinear regression. For the tested conditions, increasing initial moisture content increased the drying constant. Increasing temperature 5 and 10°C above 12°C increased the drying constant an average of 10.5 and 31%, respectively, at 12 W/m² of thermal radiation. No significant change in drying constant was found at 100 W/m² with increasing temperature. At 12 W/m² increasing the relative humidity from 40 to 50 and 60% decreased the drying constant by an average of 9.3 and 20.8% respectively. At 100 W/m² a statistically significant decrease (9.4%) occurred only for change in relative humidity from 40 to 60%. Increasing thermal radiation from 12 to 100 W/m² increased the drying constant by a factor of approximately 2. The drying constant was correlated to radiation level, vapor pressure deficit, relative humidity and temperature.

INTRODUCTION

To maximize the quality of harvested grain the preharvest exposure of the crop to adverse weather conditions must be minimized. The growing season in western Canada dictates that harvesting occurs when less than ideal drying conditions exist. Thus, minimizing the risk of damage means harvesting the grain damp and drying with mechanical systems or maximizing the rate at which the crop dries in the field before threshing.

Mathematical models of the drying and rewetting of cereal crop in a field environment will assist in developing efficient harvesting systems by highlighting areas where improvements are possible. Preharvest moisture contents of cereal grains have been correlated to environmental conditions (van Elderen and van Hoven 1973; Stewart and Lievers 1978; Smith et al. 1981) but an understanding of the basic heat and moisture transfer processes in cut and uncut wheat plants has not been developed. Work has been done with forage crops to improve in-field drying rates and model the transfer processes in the material (Kemp et al. 1972; Dyer and Brown 1977; Savoie et al. 1982).

Under field conditions drying is a complex interaction of temperature, relative humidity, radiation, initial moisture content and numerous other factors. If studies of field drying are to be effective, laboratory tests must be conducted on easily identified factors and combinations of those factors so that the field situation can be more easily studied and the effect of other known and unknown factors determined.

OBJECTIVES

The specific objective of this study was to subject rewetted wheat spikes to drying conditions and:

(1) to determine the effect of temperature, humidity, simulated solar radiation and initial moisture content on the drying constant; and

(2) to express drying constants as a function of the independent variables.

MATERIALS AND METHODS

Experimental set-up

Rewetted wheat-spikes were exposed to controlled drying conditions in an environmental chamber. Temperature and relative humidity in the chamber varied within ±1.2°C and ±5%, respectively. Simulated solar radiation was produced by two 1000-W metal-halide lamps permanently mounted above the environmental chamber. The lamps produced energy at all wavelengths in the visible spectrum. Measured spectral intensities varied with wavelength as follows: 0.24 W/(m²·nm) at 400 nm, 0.05 at 460, 0.43 at 590 and 0.04 at 650. Thermal radiation passed into the chamber through the ceiling which consisted of double-pane glass. Airflow over the samples was turbulent and ranged from 0.15 to 0.20 m/s.

Wheat spikes were placed horizontally in four parallel rows on 300 × 300-mm wire mesh racks. The racks were placed inside the chamber on electronic balances (Mettler PE1600, resolution = 0.01 g, Mettler Instruments AG, CH-8606 Greifensee, Switzerland). The masses of two racks on two balances were recorded continuously during the drying period by interfacing the balances to two portable computers (TRS-80 Model 100, Tandy Corporation).

Measurement of variables

No standard method exists for drying spikes to determine moisture content. Based on comparisons made between moisture contents determined separately for kernels, chaff and spikes, moisture contents of spikes were determined by drying 10–15 spikes at 103°C for 48 h with two replications. Moisture contents are reported on a dry mass basis unless otherwise indicated.

A humidity and temperature probe and indicator (model HM14 and HMI14, Vaisala, Helsinki) were used to measure chamber conditions. The humidity sensor (a thin-film polymer capacitor) was calibrated at relative humidities of 11 and 97% produced by saturated salt solutions. Resolutions of the readouts were 0.1°C and 0.1% relative humidity. The temperature and humidity in the chamber fluctuated sinusoidally with cycle times of 7 min and 0.75 min respectively. Reported conditions are the means of the fluctuations.

Total and net radiation were measured at the same elevation as the samples using a pyranometer (spectral range 250–2800

nm) and pyroheliometer (spectral range 200–600 nm incoming, 200–20 000 nm reflected) (Spectron Instruments, Lattabia, Calif.). Radiation levels were checked daily.

Tests

A large bulk of field-grown hard red spring wheat (*Triticum aestivum* L. 'Neepawa') was cut on 25 September 1985 and stored in a heated building at room temperature and low relative humidities where spikes dried to about 8.7% moisture content. After severing the spikes from the stems the spikes were rewetted using distilled water with a maximum daily moisture content increase of 4%. Spikes were equilibrated at 4°C for at least 10 days in sealed plastic bags before testing. Approximately 100 g of spikes were used for each test replication.

Spikes at three initial moisture contents, 22, 28 and 35%, were dried at three temperatures, 12, 17 and 22°C, and the three relative humidities, 40, 50 and 60%, at a mean radiation level of 12 ± 2 W/m² yielding 27 sets of tests with four replications of each test. Spikes at 28% initial moisture content were also dried using a mean radiation level of 100 ± 30 W/m² at the temperatures and relative humidities listed above. (Higher radiation levels do occur in the field but this was the maximum from the available equipment.) This consisted of nine sets of tests with four replications each. Except for radiation levels, test conditions correspond to actual weather conditions measured at the Winnipeg International Airport for the months of August through October.

The results as collected by the portable computers were transferred to an Amdahl mainframe system for analysis using the SAS statistical package (Statistical Analysis System (SAS) 1982).

Preliminary tests

Shrivastava (1985) determined that rewetting of wheat spikes through the stem or severed stem end was insignificant relative to direct moisture uptake through the spike surface. Versavel and Muir (1987), however, found that for both fresh and rewetted crop material severed spikes dried faster than spikes attached to the stem. Based on this, all spikes were cut from the stem at the same location to produce a uniform test material.

Preliminary tests were conducted to determine equilibrium moisture contents (EMC) of wheat spikes. Published values exist for kernels (Pixton and Henderson 1981; Duggal et al. 1982; Anonymous 1983), but relatively litle work has been done with chaff or whole spikes (Duggal et al. 1982). We measured the ratio of spike to kernel EMC at relative humidities ranging from 38 to 90% and found it to be nearly constant at 0.944 (SE = 0.0025) based on 20 values, each determined from two replications. Using this ratio equilibrium, moisture contents for kernels (Pixton and Henderson 1981) were converted to approximate EMC for whole spikes.

MATHEMATICAL ANALYSIS

An empirical drying model used by other investigators to predict drying rate of grain kernels (e.g., Smith et al. 1981) was used to correlate the collected data:

$$\frac{M - M_e}{M_o - M_e} = \exp(-kt) \qquad (1)$$

where

M = moisture content (% db),
M_e = equilibrium moisture content (% db),
M_o = initial moisture content at time $t = 0$ (% db),
t = time (h), and
k = drying constant (h^{-1}).

A similar equation:

$$\frac{M - M_e}{M_o - M_e} = \exp(-kt)^N \qquad (2)$$

where N is a constant, has been used in recent work (e.g., Misra and Brooker 1980; Sokhansanj et al. 1984) because it results in a better fit. Nonlinear regressions based on Eq. 2 typically had residual sums of squares which were 10–20% of residual sums of squares computed based on Eq. 1. However, both models predicted the drying of the spikes well. Equation 2 was avoided because it makes comparison of the drying constants difficult. In addition, Eq. 2 has no theoretical basis and is only used to reduce the error of fit.

Procedure NLIN (SAS 1982), which produces a least-squares estimate of the parameters of a nonlinear model was used to fit Eq. 1 to the collected data. Using procedure STEPWISE (SAS 1982) the measured and calculated parameters; radiation, temperature, vapor pressure deficit, relative humidity, and initial moisture content, were correlated to the computed drying constants. Only terms producing an F-statistic greater than 10% were included in the model. Both linear and exponential models were examined.

RESULTS AND DISCUSSION

The nonlinear form of Eq. 1 statistically fit to the collected data consistently underestimated drying for the first 2 h and overestimated it for the last 2 h of drying. Despite this, the accuracy of the prediction was good for all tests ($R^2 \geqq 0.993$).

Increasing thermal radiation levels from 12 to 100 W/m² almost doubled the drying rate (Table I). Yet 100 W/m² is low compared with the average solar radiation for a sunny day on a horizontal surface in Winnipeg at noon in August of 625 W/m² (Environment Canada 1982). An important variable which was not measurable and could account for the increased radiation is convection. Natural convection currents, in addition to surrounding airflows, would be set up by the warm spikes enhancing moisture loss. But, based on a comparison of the Reynolds and Grashof numbers for the experimental conditions, forced convection was probably the predominant transfer process (Incropera and DeWitt 1985). Increased moisture diffusion in the spikes exposed to radiation would also occur. Test conditions did not allow the magnitude of those factors to be measured. Further work should determine the magnitude of these factors on the drying constant.

Initial moisture content had an inconsistent effect on the drying constant. At 22°C the drying constant increased with initial moisture content (Table I). The increase in the drying constant was not as large or was insignificant at the 5% level at the lower temperatures. A larger drying constant with increased moisture content can intuitively be expected since the vapor deficit is increased and more moisture is initially available at the surface of the spikes. The inconsistency of the effect of initial moisture content does not allow any firm observations to be made. At 22°C, the drying constant decreased with increased relative humidity, but at 12 and 17°C the drying constant decreased only slightly or remained constant. Increases in relative humidity from 40 to 50 and 60% resulted in 9 and 21% average decreases in drying constant. Under the elevated radiation level an increase in relative humidity from 40 to 50% caused

Table I. Summary of fitted drying constants† (h^{-1}) to data collected for drying rewetted wheat spikes under simulated environmental conditions

Mean thermal radiation (W/m^2)	Initial moisture content (dry basis) (%)	Air temperature (°C)								
		12.2 (±0.31)			16.9 (±0.75)			21.8 (±0.86)		
		Relative humidity (%)								
		40	50	60	40	50	60	40	50	60
12	22	0.100 (0.0039)‡	0.103 (0.0038)	0.073 (0.0035)	0.100 (0.0043)	0.103 (0.0049)	0.100 (0.0045)	0.153 (0.0064)	0.093 (0.0039)	0.087 (0.0041)
12	28	0.100 (0.0035)	0.106 (0.0038)	0.080 (0.0028)	0.103 (0.0043)	0.100 (0.0059)	0.100 (0.0047)	0.169 (0.0071)	0.130 (0.0074)	0.111 (0.0050)
12	35	0.100 (0.0036)	0.100 (0.0038)	0.089 (0.0030)	0.117 (0.0044)	0.106 (0.0037)	0.100 (0.0037)	0.154 (0.0058)	0.120 (0.0037)	0.100 (0.0036)
100	28	0.199 (0.0111)	0.200 (0.0077)	0.200 (0.0085)	0.184 (0.0116)	0.203 (0.0075)	0.167 (0.0071)	0.213 (0.0106)	0.200 (0.0064)	0.172 (0.0084)

†Nonlinear fit of Eq. 1 to data from four test replications, 96 observations.
‡Values in parentheses are asymptotic standard errors.

an insignificant increase of 2% in drying constant while an increase to 60% caused a significant decrease of 9% in the drying constant. At 12 and 17°C individual comparisons of the drying constant between the relative humidities used indicate in, some instances, an increasing drying constant with relative humidity. These increases are less than 6% and were considered insignificant and attributed to biological and random variation. Increasing temperature by 5 and 10°C, above 12°C resulted in average increases of 11 and 31% in the drying constant at the low radiation level. Under elevated radiation average decreases in the drying constant of 8 and 2%, respectively, were observed for temperatures above 12°C but the decreases were not statistically significant. The effect of increasing ambient temperature was probably masked by the thermal radiation. This suggests a need for further work.

Moist spikes initially subjected to drying conditions probably have an adequate supply of moisture on their surfaces so that they approximate a free water surface. As drying progresses, surface moisture becomes a function of the unknown moisture-diffusion properties of the spikes. Vapor pressure deficit at the start of drying was defined as the difference between the vapor pressure of the drying air and the saturated vapor pressure corresponding to a free water surface. Calculations were done using ASAE Data D271.2 (Anonymous 1983). At 22°C and radiation of 12 W/m^2, increasing the relative humidity from 40 to 50% and from 40 to 60% gave average decreases of 28 and 37% in the drying constant while the vapor pressure deficit decreased 17 and 33%. At the two lower temperatures there appeared to be little or no correlation. For decreases in vapor pressure deficits of 17 and 33%, corresponding changes in drying constant were +3 and −19% at 12°C and −3 and −6% at 17°C. Possibly, diffusion in the spikes limited moisture loss at the lower temperatures. Spikes, being biological materials, may have large changes in their moisture diffusion properties in the temperature range examined. Vapor pressure deficit was included in trying to correlate the drying constant with measured environmental data.

The following correlation was developed from the experimental data:

$$k = -1.660 + 0.000833\,RAD + 0.000454\,Pd{\cdot}T + 0.0766\ln(RH) + 488.0/T \quad (3)$$

where

RAD = total radiation (W/m^2),
Pd = vapor pressure deficit (kPa),
RH = relative humidity (decimal) and
T = absolute temperature (K).

The basis for selecting Eq. 3 over an exponential version was the R^2 values. Equation 3 had an R^2 of 0.855 while the best fit exponential model had only a slightly smaller value of 0.814. The exponential version correlated the above variables to the natural log of k.

In developing a model to predict moisture during field drying Smith et al. (1981) used Eq. 1 and a drying constant which was exponentially related to the inverse of the absolute temperature. This work was based on laboratory measurements of thin layer drying of threshed wheat. The drying constants used by Smith et al. (1981) for 12, 17 and 22°C were 0.120, 0.168 and 0.225 h^{-1}, respectively. At 12°C their drying constant is 20% greater than ours. At 17 and 22°C our predicted drying constants do not show the same magnitude of increase. The differences could be caused by differences in cultivar, maturity and drying conditions. Their equation was evaluated for digital simulation of drier performance. Crampin and Dalton (1971), also using Eq. 1 as their model, found that the drying constant was a constant equal to 0.04 h^{-1}. This value was based on hourly measurements in standing wheat and barley over four seasons. This constant is substantially smaller than drying constants determined for the tests conducted in this study. This leaves the possibility that fresh spikes dry much slower than rewetted spikes. Work presently being conducted using the equipment described and a limited quantity of fresh Neepawa wheat spikes indicates a similar trend (data not presented).

The drying constants used by Smith et al. (1981) do not include as an independent variable the effect of solar radiation incident upon the crop material, while Crampin and Dalton (1971) have the effect implicitly included in their constant. Results from our work indicate that the drying constant is increased by increasing the level of thermal radiation incident upon the spikes (Table I).

In spikes exposed to thermal radiation a temperature rise of 1–3°C above ambient was found using 30-gauge thermocouples inserted between the kernel and glume. This temperature rise may be the main reason for the observed increase in the drying constant when the spikes were exposed to elevated radiation

levels. Temperature rises 7–8°C above ambient have been measured at the top of swaths and at the swath level (Prasad et al. 1978; Singh et al. 1984). Based on measurements made in the laboratory, efforts to maximize the temperature of material in the field could improve field drying. The increased temperatures would increase the intensity of convection currents set up and also increase moisture diffusion in the spikes.

Rewetting of spikes in the field occurs due to rainfall and condensation. The rewetted spikes used in our tests would be representative of swathed crop subjected to intermittent rain. If moisture contained in fresh spikes is lost more slowly than moisture reabsorbed during rainfall, then it would be advantageous to have a swath design which enhances moisture loss while minimizing any possible rewetting of the spikes. This is an area which requires further investigation.

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REFERENCES

ANONYMOUS. 1983. Agricultural Engineers Yearbook of Standards, 13th ed. Am. Soc. Agric. Eng., St. Joseph, Mich.

CRAMPIN, D. J. and G. E. DALTON. 1971. The determination of the moisture content of standing grain from weather records. J. Agric. Eng. Res. 16(1):88–91.

DUGGAL, A. K., W. E. MUIR and D. B. BROOKER. 1982. Sorption equilibrium moisture contents of wheat kernels and chaff. Trans. ASAE (Am. Soc. Agric. Eng.) 25(4):1086–1090.

DYER, J. A. and D. M. BROWN. 1977. A climatic simulator for field-drying hay. Agric. Meteorol. 18:37–48.

ENVIRONMENT CANADA. 1982. Canadian climate normals, 1951–1980. Atmospheric Environment Services, Toronto, Ont. Vol. 1.

INCROPERA, F. P. and D. P. DeWITT. 1985. Fundamentals of heat and mass transfer. 2nd ed. John Wiley & Sons, Toronto, Ont. 802 pp.

KEMP, J. G., G. C. MISENER and W. S. ROACH. 1972. Development of empirical formulae for drying of hay. Trans. ASAE (Am. Soc. Agric. Eng.) 15(4):723–725.

MISRA, M. K. and D. B. BROOKER. 1980. Thin-layer drying and rewetting equations for shelled yellow corn. Trans. ASAE (Am. Soc. Agric. Eng.) 3(5):1254–1260.

PIXTON, S.W. and S. M. HENDERSON. 1981. The moisture content- equilibrium relative humidity relationships of five varieties of Canadian wheat and of Candle rapeseed at different temperatures. J. Stored Prod. Res. 17:187–190.

PRASAD, D. C., W. E. MUIR and H. A. H. WALLACE. 1978. Characteristics of freshly harvested wheat and rapeseed. Trans. ASAE (Am. Soc. Agric. Eng.) 21(4):782–784.

SAVOIE, P., C. A. ROTZ, H. F. BUCHOLTZ and R. C. BROOK. 1982. Hay harvesting system losses and drying rates. Trans. ASAE (Am. Soc. Agric. Eng.) 25(3):581–585, 589.

SHRIVASTAVA, A. M. 1985. Moisture absorption and movement in swathed wheat plants. Unpublished M.Sc. Thesis. Dept. Agric. Eng., University of Manitoba, Winnipeg, Man. 88 pp.

SINGH, D., S. SOKHANSANJ and D. BERGH. 1984. Effect of harvest date and method on drying rate of wheat. Paper no. 84–207. Presented at the 1984 Ann. Mtg. Can. Soc. Agric. Eng.

SMITH, E. A., P. H. BAILEY and G. W. INGRAM. 1981. Prediction of the field moisture content of mature barley and wheat by commonly used drying equations. J. Agric. Eng. Res. 26:171–178.

SOKHANSANJ, S., D. SINGH and J. D. WASSERMAN. 1984. Drying characteristics of wheat, barley and canola subjected to repetitive wetting and drying cycles. Trans. ASAE (Am. Soc. Agric. Eng.) 27(3):903–906, 914.

STATISTICAL ANALYSIS SYSTEM. 1982. SAS user's guide: Statistics, 1982 edition. SAS Institute, Inc., Cary, N.C.

STEWART, D. W. and K. W. LIEVERS. 1978. A simulation model for the drying and rewetting processes of wheat. Can. Agric. Eng. 20:53–59.

van ELDEREN, E. and S. P. J. H. van HOVEN. 1973. Moisture content of wheat in the harvest period. J. Agric. Eng. Res. 18:71–73.

VERSAVEL, P. A. and W. E. MUIR. 1987. Crushing of swathed stems to improve field drying of cereal crops. Can. J. Plant Sci. 67:637–644.