

Equilibrium moisture content of lentils

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Cenkowski, S., Sokhansanj, S. and Sosulski, F.W. 1989. **Equilibrium moisture content of lentils**. *Can. Agric. Eng.* **31**: 159-162. Equilibrium moisture contents of Laird lentils for relative humidities of 11-90% in the range of 5-50°C were determined. A nonlinear regression was performed to estimate the constants of the modified Henderson equation and the Chung equation. It was concluded that both equations represented the equilibrium relative humidity-moisture content relationship up to 80% relative humidity but the modified Henderson equation gave the best fit to the experimental data with constants K, C, and N as a function of temperature.

INTRODUCTION

A knowledge of the equilibrium moisture content of a biological material is essential for the efficient operation of systems for wetting, drying, or storing the material. The equilibrium moisture content (EMC) for a given environment may be defined as the moisture content of the material when left in that environment for an infinite period of time.

Lentils are a well-established crop in Western Canada with most of the crop being grown in Saskatchewan. In 1987, more than 300 000 t of lentils were produced on the Prairies (Statistics Canada 1988) with a value of more than \$130 million dollars.

Equilibrium moisture content of lentils has not been investigated. Rao and Pfof (1980) developed the equilibrium isotherms for the seeds of 20 agricultural crops. They concluded that bringing air to equilibrium with a seed of fixed moisture content (ERH method) was simpler and faster than bringing a sample of seed to equilibrium with air of fixed relative humidity (EMC method).

One of the best known relationships for predicting the EMC of cereal grains is the semi-empirical model proposed by Henderson (1952). Henderson's equation, in its original form, proved to be inadequate for cereal grains and a number of empirically established modifications of the Henderson equation have been proposed (Day and Nelson 1965; Thompson 1967).

American Society of Agricultural Engineers Data D245.4 (ASAE 1987) lists the following equations to describe the EMC-ERH for agricultural grains:

The modified Henderson equation:

$$\text{ERH} = 1 - \exp [-K(T+C) (100 \text{ EMC})^N] \quad (1)$$

The Chung equation:

$$\text{ERH} = \exp \left[\frac{-A}{T+C} \exp (-B \text{ EMC}) \right] \quad (2)$$

where T is grain temperature (°C), EMC is decimal dry basis moisture content, and ERH is decimal relative humidity. Constants A, B, C, K, and N are product dependent. The American Society of Agricultural Engineers (1987) lists the constants for the seeds of 11 crops excluding lentils.

The objectives of this investigation were to experimentally determine the sorption equilibrium moisture content of the large-seeded lentil cultivar Laird, and to estimate the product-dependent constants of the modified Henderson equation and of the Chung equation.

EXPERIMENTAL PROCEDURE

Both EMC and ERH procedures were used in this study. The ERH method was based on bringing a small mass of air into contact with a relatively large mass of grain at a constant temperature. The EMC method was based on drying a thin layer of grain in a constant temperature and relative humidity environment until the grain reached equilibrium with the drying air. The experimental results of both methods were combined to estimate the product-dependent constants.

Equipment

A schematic diagram of equipment used in the ERH procedure is shown in Fig. 1. The sample container was a plastic cylinder-aspirator holding 2 kg of lentils. Inside the cylinder, a wire screen supported the sample and provided a plenum beneath the grain mass. A variable-speed aquarium air pump provided air circulation. A chilled mirror hygrometer model DEW-10 (General Eastern Instruments, Watertown, MA) was used as a humidity sensor to measure the dew point temperature. The DEW-10 hygrometer had an accuracy of $\pm 0.7^\circ\text{C}$ within the dew point measurement range from -23.3°C to $+60^\circ\text{C}$ and ambient dry bulb temperature range from 0 to 60°C . The relative humidity range of DEW-10 hygrometer for 0°C of ambient temperature was from 18 to 90% RH and for 60°C was from 8 to 90% RH.

The dew cell was mounted underneath the lid of the container but above the grain surface (Fig. 1). The air pump was adjusted to provide an air velocity of approximately 0.2 m/s ($\sim 14 \text{ m}^3/\text{h}$). Dry bulb temperature was measured by an RTD sensor mounted at the intake port of the dew cell. Temperatures below and above the grain were sensed by copper-constantan thermocouples with a nominal accuracy of 1.0°C . The dew cell and the air pump generated sufficient heat to raise the recirculating air temperature by about $1-2^\circ\text{C}$. The excess heat was removed by immersing the coiled copper tube in a water bath.

Equilibrium moisture content of lentil at specific combinations of temperature and relative humidity were determined by drying the samples for 48 h or more in a horizontal thin layer dryer (Fig. 2). The design of the drying apparatus has been described in detail by Sokhansanj et al. (1983). In this apparatus the relative humidity was measured by three lithium chloride sensors (YSI model 9400 Dew-cell) with a relative humidity measurement range of 11-100%. The sensors were placed upstream from the grain sample. The maximum possible error in

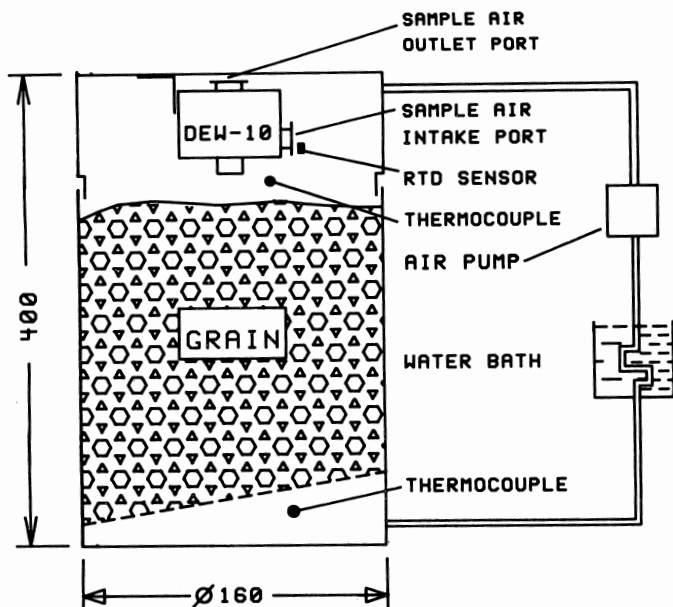


Figure 1. Schematic diagram of the test apparatus used in ERH procedure.

sensing dew point temperature in the range -12 to 30°C was 1.0°C . For a stable response, the recommended optimum air velocity was 0.1 – 1.0 m/s and the air velocities at the sample and dew point sensors were measured at 0.4 m/s. The wet and dry bulb temperatures were sensed by five copper-constantan thermocouples installed in the drying chamber.

Preparation of samples

Both freshly harvested seeds and commercial seeds of lentil were used in the EMC-ERH experiments. Fresh seeds were harvested between Aug. 14 and 23, 1987. The moisture contents of the seed samples ranged from 33.5 to 12.5% WB, respectively, at the two dates. These fresh samples were sealed in plastic bags and stored in a freezer maintained at -15°C .

In addition, a 20 -kg sample of clean and dry (10.4% moisture WB) Laird lentil from the 1986 crop was purchased from a commercial source. Both fresh and dry seed samples were graded as

Canada No. 1 according to the Canadian Grain Commission grading standards.

Prior to tests, a sample of approximately 2 kg of the above dry grain was dampened to a predetermined moisture content by spraying distilled water on the seed while tumbling. The sample was stored in a sealed container for 24 h at room temperature with occasional tumbling to insure uniform distribution of moisture. The dampened samples were then transferred to a temperature-controlled room for 2 wk at 5°C . For moisture contents of less than 10% WB (ERH procedure), seeds were dried with heated air (35°C), cooled gently in air, and stored in sealed bags.

ERH procedure

Before each test, samples were conditioned in plastic bags for 24 h in the temperature-controlled room where the tests were performed. The temperature of this room was maintained within $\pm 0.5^{\circ}\text{C}$. The contents of the plastic bags were emptied into the sample holder of the apparatus (Fig. 1) and the air pump started. Outputs of the dew-cell and thermocouples were recorded hourly by a data logger. Data collection continued until the dew point and dry bulb temperatures approached a constant value and remained unchanged for at least 4 h. The grain moisture content was determined before and after completion of a test by the convection oven method at 105°C for 24 h as outlined in ASAE Standard S352.1 (ASAE 1987).

EMC procedure

Approximately 120 -g samples of grain with initial moisture content of 22% WB were dried in the thin-layer dryer (Fig. 2) until the grain moisture content approached equilibrium and the weight of a sample remained constant for at least 4 h. Samples were dried at 30 and 40°C at different RH up to 80% and at 50°C at RH from 8 to 56% . The sample was divided into two lots from which a 20 -g grain sample was taken for oven moisture measurement.

RESULTS AND DISCUSSION

The experimental data for experiments conducted at 5 , 20 , 30 , 40 , and 50°C are presented in Figs. 3–6. The sorption data of fresh and rewetted (commercial) lentil were compared at 5°C

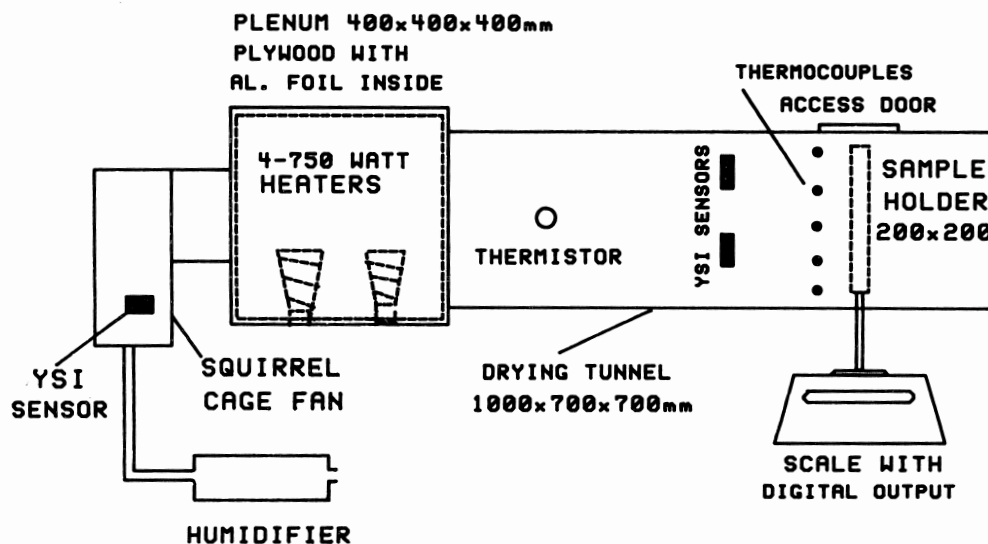


Figure 2. Schematic diagram of the thin layer drying apparatus used in EMC procedure. Source: Sokhansanj et al. (1983).

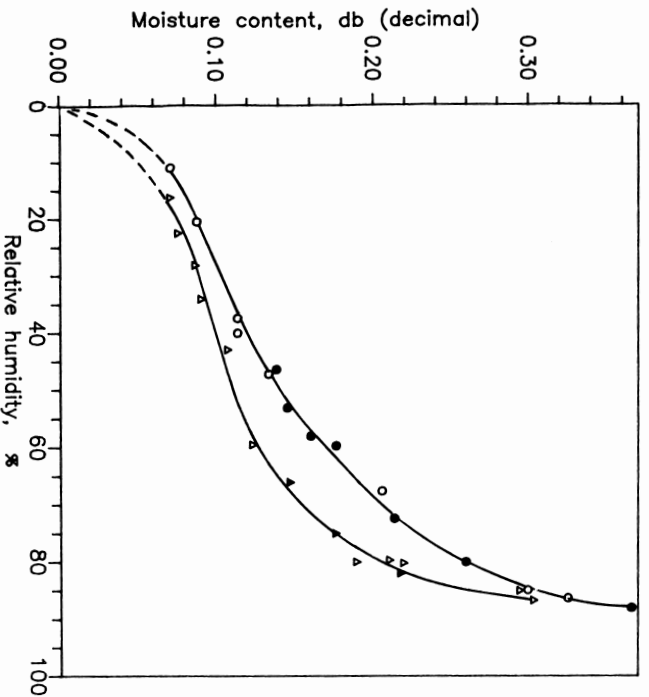


Figure 3. Sorption data of fresh (●, ▲) and rewetted (○, △). Laird lentil for 5°C (○, ●) and 30°C (△, ▲).

using ERH procedure and at 30°C using EMC and ERH procedure. The results are presented in Fig. 3. The solid triangles and circles stand for equilibrium data obtained for fresh lentil. The lines in Fig. 3 are drawn manually and fit adequately points obtained from fresh and rewetted lentil. Therefore, it was concluded that both, the rewetted and freshly harvested samples of lentil, can be used for the experiment.

A nonlinear least-squares program (Marquardt 1963) was used to fit the modified Henderson and Chung equations to the experimental data. The constants of Eqs. 1 and 2, the standard deviation of the estimates, the sum of squares of residuals, and the standard error of ERH estimate are given in Table I. The sum of squares of residuals represents the difference between the experimental data and the data predicted by the equations. The modified Henderson equation with coefficients K, C, and N as function of temperature produced the smallest residuals.

Figures 4 and 5 show the experimental data and the equilibrium curves produced by Eq. 1 for the range from 5 to 50°C. The difference between two figures is that in Fig. 4 mean values of coefficients K and N were used in the calculation, whereas the coefficient C was calculated as a function of temperature. In Fig. 5 coefficients K, C, and N have been calculated from temperature functions.

The average coefficients K and N in Eq. 1 do not predict as well within the range 5–50°C, but results are fairly good for 30°C. Standard error of estimate of ERH was 5.4%. Ajibola (1986) presented desorption isotherms of garri based on the modified Henderson equation and obtained a standard error of estimate of ERH of 4.7%.

When coefficients K, C, and N are considered as a temperature function (Table I) then the calculated results for the range from 20 to 80% of RH were very close to the experimental data for temperatures from 30 to 50°C. The predicted results of EMC of lentil for 5°C were higher than experimental points and at 20°C they were slightly lower. The standard error of estimate of ERH was 4.83%.

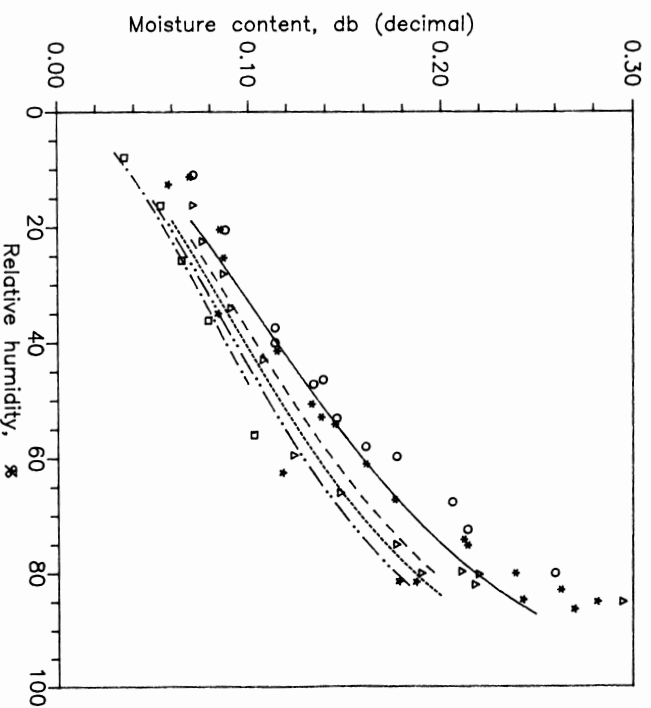


Figure 4. Experimental data and the predicted isotherms using the modified Henderson equation with the equation average coefficients K and N. Temperature: (○) 5°C ———; (*) 20°C - - - -; (△) 30°C - · - · -; (*) 40°C ———; (□) 50°C ———.

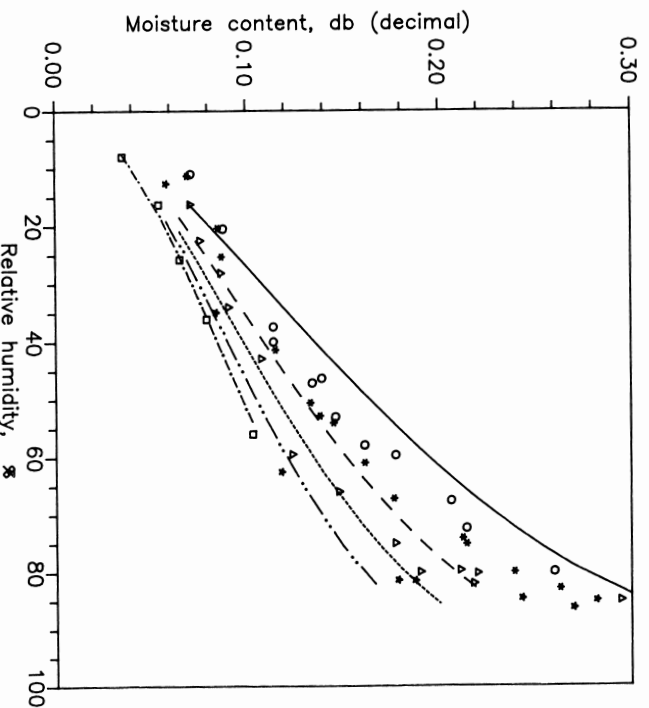


Figure 5. Experimental data and the predicted isotherms using the modified Henderson equation with the equation coefficients K, C, and N as a function of temperature. Temperature: (○) 5°C ———; (*) 20°C - - - -; (△) 30°C - · - · -; (*) 40°C ———; (□) 50°C ———.

Figure 6 shows the experimental results and the equilibrium curves produced by Eq. 2 in the range from 5 to 50°C. The calculated results for the range from 20 to 70% are very close to the experimental data for the temperatures 20 and 30°C. The standard error of estimate was 5.76%.

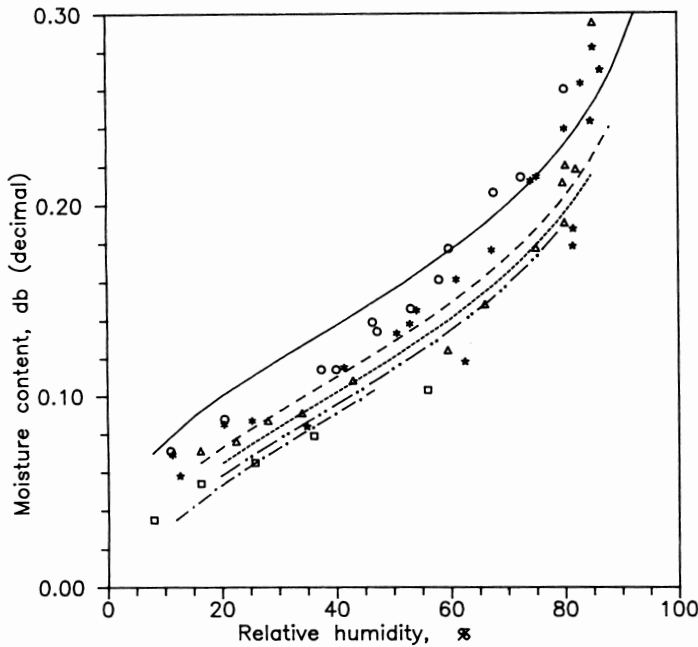


Figure 6. Experimental data and the predicted isotherms using the Chung equation with modified coefficient *A* as a function of temperature. Temperature: (○) 5°C ——— ; (*) 20°C — — — ; (△) 30°C - - - - - ; (*) 40°C — · — · — ; (□) 50°C — · — · —

Table 1. Estimated constants for the EMC-ERH equations in the range of 20-80% of relative humidity

| <i>Modified Henderson equation</i> | | | | |
|--|---------|---------------------|-------|-------|
| K | | C | N | |
| Mean | ± SD | | Mean | ± SD |
| 0.00034 | 0.00094 | $C = -0.75T + 17.4$ | 1.797 | 0.215 |
| Sum of square of residuals for ERH 29.4 | | | | |
| Standard error of ERH estimate 5.42% | | | | |
| <i>Modified Henderson equation with all coefficients as functions of temperature</i> | | | | |
| $K = -0.000005T + 0.00043$; $C = -0.75T + 17.4$; | | | | |
| $N = 1.57 \exp(0.0061 T)$ | | | | |
| Sum of square of residuals for ERH 23.2 | | | | |
| Standard error of ERH estimate 4.83% | | | | |
| <i>Chung equation with modified coefficient A</i> | | | | |
| A | B | | C | |
| | Mean | ± SD | Mean | ± SD |
| $A = 2.4T + 97.1$ | 15.1 | 4.2 | 10.0 | 24.0 |
| Sum of square of residuals for ERH 33.2 | | | | |
| Standard error of ERH estimate 5.76% | | | | |

When estimated constants were considered as a temperature function, both equations (Eqs. 1 and 2) predicted isotherms up to a relative humidity of 80% reasonably well but beyond this point they under-predicted the equilibrium moisture content. The experimental equilibrium moisture content increased rapidly at relative humidities in the range of 80–90%. The predicted equilibrium moisture did not show such a rapid increase at this range (80–90%) of relative humidity.

Equilibrium data were not generated above 90% because of the performance characteristics of the chilled mirror hygrometer model DEW-10 in which the maximum measurable relative humidity was limited to 90%.

CONCLUSIONS

Comparing the two equations, we found that the modified Henderson equation, with coefficients *K*, *C* and *N* as a function of temperature, had smaller sum of squares of residuals than the same Henderson equation with averaged coefficients *K* and *N* or the Chung equation. When estimated constants were considered as a temperature function, both equations (Eqs. 1 and 2) predicted isotherms up to a relative humidity of 80% reasonably well. None of these equations had a good fit to the experimental data between 80 and 90% relative humidity.

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REFERENCES

- AJIBOLA, O. O. 1986. Desorption isotherms of gari from 40°C to 70°C. *J. Agric. Eng. Res.* 35: 207–210.
- AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS. ASAE, St. Joseph, MI.
- DAY, D. L. and G. L. NELSON. 1965. Desorptions for wheat. *ASAE (Am. Soc. Agric. Engrs.)* 8: 293–297.
- HENDERSON, S.M. 1952. A basic concept of equilibrium moisture. *Agric. Eng.* 33: 29–31.
- MARQUARDT, D. M. 1963. An algorithm for least squares estimation of nonlinear parameters. *J. Soc. Industr. Appl. Mat.* 11: 431–441.
- RAO, V. G. and H. B. PFOST. 1980. Physical properties related to drying 20 food grains. *ASAE Paper no. 80-3539, Am. So. Agric. Engrs. MI.*
- SOKHANSANZJ, S., W. P. LAMPMAN, and J. D. MACAULEY. 1983. Investigation of grain tempering on drying tests. *Trans ASAE (Am. Soc. Agric. Engrs.)* 26: 293–296
- STATISTICS CANADA. 1988. Alberta Agriculture, Manitoba Agriculture, Saskatchewan Agriculture, Fact Sheets.
- THOMPSON, T. L. 1967. Predicted performances and optimal designs of convection grain dryers. Ph.D. Thesis, Purdue University, Lafayette, IN.