Equilibrium Moisture Content of White Beans

D. H. HUTCHINSON and L. OTTEN, School of Engineering, University of Guelph, Ontario N1G 2W1

ABSTRACT

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Moisture desorption isotherms were determined for "seafarer" white beans, *Phaseolus vulgaris*. Saturated salt solutions were used to maintain constant-humidity environments in which samples were allowed to equilibrate. Data were obtained at temperatures of 16, 32, 38, and 49°C. Relative humidities were varied from approximately 20 to 80% at each temperature. Several variations of the Henderson and Chung-Pfost equations were chosen from the large number of available expressions for predicting equilibrium moisture content. Good fits of the experimental data were obtained when both the Henderson and the Chung-Pfost equations with temperature-dependent parameters were used.

The equilibrium moisture content (EMC) is an important material property that has a significant impact on the handling, processing, and storage of all hygroscopic materials. Equilibrium moisture is the moisture content at which the atmospheric and material water vapor pressures are equal and no adsorption or desorption occurs.

Numerous investigations have been conducted to determine the equilibrium moisture content of a wide variety of hygroscopic materials. A number of theoretical, semitheoretical, and empirical equations have been developed and used in the analysis of EMC data. Chirife and Iglesias (1978) presented a comprehensive review of 23 existing EMC equations. Of the available EMC equations, only a few have been used successfully in studies of agricultural materials. Most equations apply over only limited ranges of relative humidities.

Kumar et al (1978) reported that the BET model was satisfactory describing EMC isotherms for intact corn ears and component parts for relative humidities less than 50%. Gustafson and Hall (1974) found that the Harkins and Jura equation was unsatisfactory for predicting equilibrium moisture levels for shelled corn at relative humidities below 30% and that the Smith equation was valid only for relative humidities above 30%.

The Henderson equation (Henderson 1952) has been widely applied in the analysis of equilibrium moisture data for various materials. Gustafson and Hall (1974) found that the Henderson equation underpredicted equilibrium moisture content at relative humidities above 85%. Similarly, Alam and Shove (1973) showed that the Henderson equation did not give acceptable predictions of EMC at relative humidities above 80% in their study of soybeans.

Several variations of the Henderson equation that have been used should be noted. For example, Thompson (1972) modified the effect of temperature with the addition of an empirical constant.

A four-constant modification was proposed by Day and Nelson (1965) to model moisture isotherms for wheat. They expressed the original two coefficients as exponential functions of temperature. Kumar et al (1978) used linear functions to model the observed temperature dependence of the coefficients.

Chung and Pfost (1967) proposed a two-parameter theoretical isotherm equation that has also been used successfully to fit equilibrium moisture content data for a variety of hygroscopic materials. As was the case for the Henderson equation, modifications of the original equation have been proposed. Dunstan et al (1973) developed equations that expressed the temperature dependence of the Chung-Pfost coefficients. Pfost et al (1976) modified the original equation by introducing an additional parameter to change the effect of temperature.

Although a considerable amount of data are available for many agricultural crops, little information was found in the literature for white beans. Because we are interested in the effect of drying and storage on the quality of edible beans and grain corn (Brown et al 1979), a project was initiated with the objectives of obtaining equilibrium moisture content data for white beans, and of developing a prediction equation for use in drying models.

MATERIALS AND METHODS

White beans, *Phaseolus vulgaris*, of the "seafarer" variety were used in this study. The beans were grown in southern Ontario in 1981 and were harvested at a moisture content of approximately 32% (d.b.). The beans were frozen immediately after harvesting and were stored in a freezer at −10°C until needed. Only undamaged, clean beans with no evidence of mold growth were selected for testing.

Equilibrium moisture content data were obtained by allowing a sample of whole beans to equilibrate under conditions of controlled humidity and temperature. Saturated salt solutions were used to maintain a constant-humidity environment. The use of saturated salt solutions to control humidity in EMC studies is well documented (Hall 1957, Brooker et al 1974).

Wide-mouth 455-ml glass canning jars were used as controlled-humidity chambers. Sample baskets were constructed of aluminum mesh and were coated with urethane spray for corrosion protection.

Desorption equlibrium moisture isotherms were obtained for temperatures of 49, 38, 32, and 16°C. Table I lists the five salts used and the characteristic relative humidities produced above the solutions at the specified temperatures. Values of relative humidities given in Table I were determined from data given in Perry and Chilton (1973) and in Rockland (1960). Two samples were tested for each combination of temperature and humidity, using two different sealed jars in the same isothermal environment. Hence a total of 40 values of equilibrium moisture content were obtained experimentally.

A sample of whole, undamaged white beans was spread in a single layer that covered the bottom of the sample basket. Air was able to circulate freely around the entire sample, thus reducing the time required to reach equilibrium. The initial sample mass was measured, and the sample was then sealed in a jar above a saturated salt solution and placed in an isothermal environmental chamber. The sample was removed for weighing at intervals of approximately three days. The sample was considered to have reached equilibrium when the change in sample mass between several successive measurements was 0.01 g or less.

The typical sample had a total initial mass of approximately 13 g at 32% moisture (d.b.). A change of 0.01 g in the above sample corresponds to a change of about 0.1 percentage points in the dry-basis moisture content of the sample.

The final moisture content of the sample was determined after

TABLE I
Relative Humidities Above Saturated Salt Solutions

Temp. (°C)	$KC_2H_3O_2$	$MgCl_2\cdot 6H_2O$	$Mg(NO_3)\cdot 6H_2O$	NaCl	$(NH_4)_2SO_4$
16	23.6	33.8	56.3	75.5	81.4
32	21.5	32.6	51.9	75.6	80.0
38	20.4	32.3	50.4	75.3	79.7
49	18.2	31.6	47.3	74.8	79.1

equilibrium had been achieved, using the standard ASAE oven-drying method (ASAE S352); ie, the sample was dried in an oven at 103°C for three days (72 hr).

RESULTS AND DISCUSSION

Experimental Data

The time required for a sample to obtain equilibrium varied, with low-temperature and low-humidity conditions requiring the longest times. The samples maintained at 16°C and 23% relative humidity required 31 days to reach equilibrium moisture conditions. Mold was observed to develop on beans kept at 80% relative humidity at temperatures of 38 and 49°C. Mold growth was not extensive at the above conditions and was presumed not to have a significant impact on the final moisture content of the sample.

There was very good agreement between values of equilibrium moisture content determined for the pairs of samples that were allowed to equilibrate under identical conditions. The maximum difference noted was 0.3 percentage points in the dry basis equilibrium moisture contents between duplicate samples. In most cases, the difference was 0.1 percentage points or less. The average experimental observations are shown in Figs. 1–4.

Prediction Equations

The Henderson and the Chung-Pfost equations have been reported to give the best predictions of equilibrium moisture content for agricultural materials over wide ranges of temperatures and relative humidities. In addition, both equations offer the advantage that they may be solved explicitly for either equilibrium moisture content or for relative humidity (water activity). For these reasons, both equations were selected. The Chung-Pfost equation

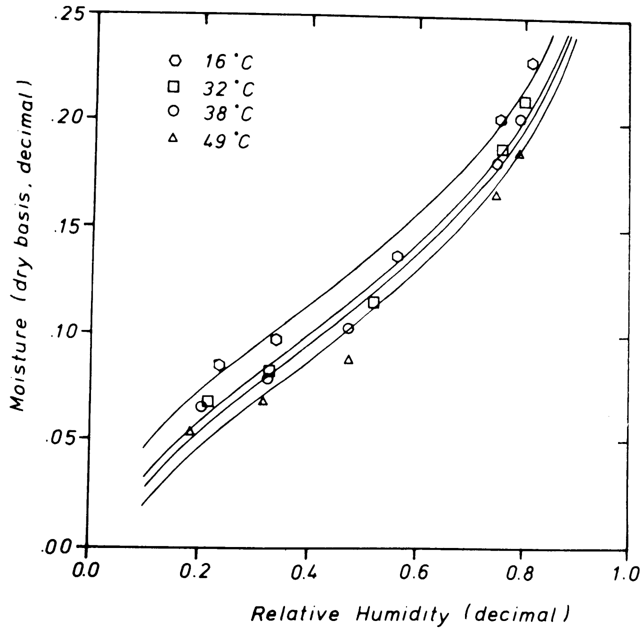

Fig. 1. Equilibrium moisture isotherms predicted for white beans by Chung-Pfost equation with constant coefficients.

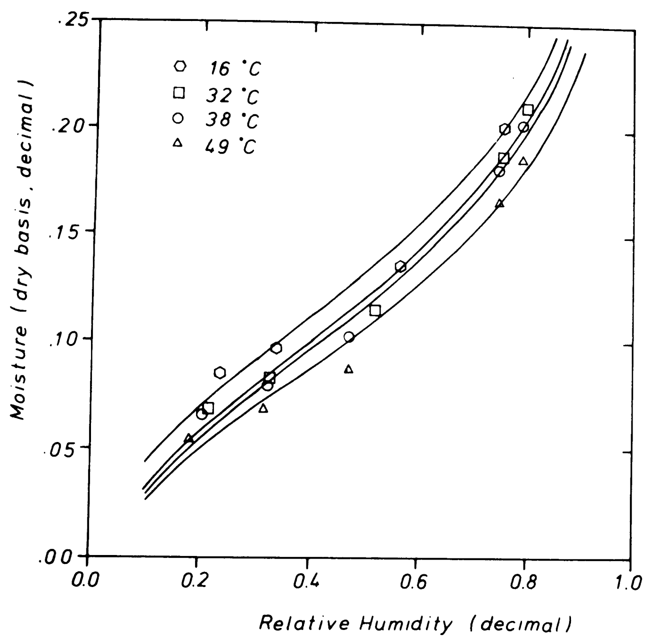

Fig. 2. Equilibrium moisture isotherms predicted for white beans by Chung-Pfost equation with variable coefficients.

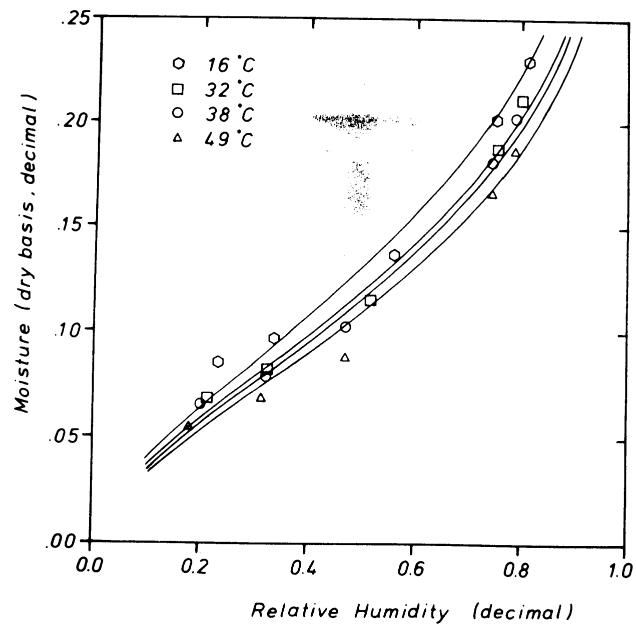

Fig. 3. Equilibrium moisture isotherms predicted for white beans by Henderson equation with constant coefficients.

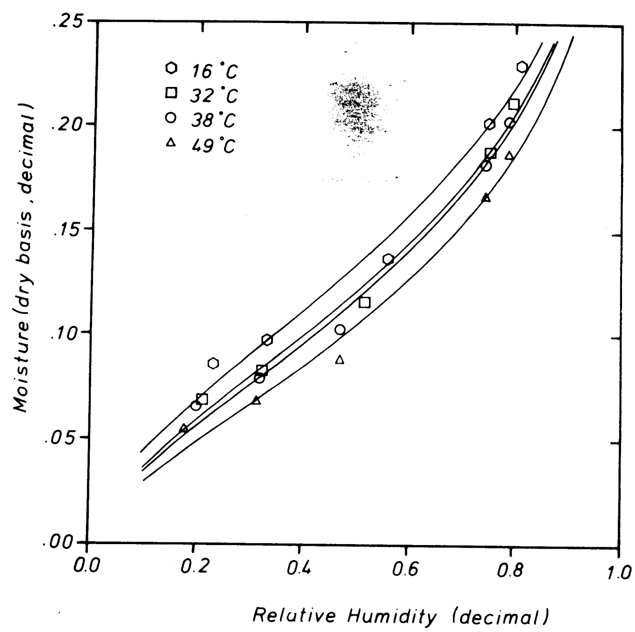

Fig. 4. Equilibrium moisture isotherms predicted for white beans by the Henderson equation with variable coefficients.

was expressed as

$$Me = [\ln A - \ln(T + C) - \ln(-\ln(rh))] (1/B) \qquad (1)$$

Parameters in equations 1 and 2 are defined in Table II.

Two approaches were used to determine the parameters A, B, and C. It was first assumed that the parameters were temperature independent, and a regression was performed for all data points from all four isotherms. The Statistical Analysis System (SAS) procedure nonlinear regression (Helwig and Council 1979) was employed in the analysis.

The second approach included the assumption that the parameters A, B, and C were temperature dependent. Regressions were performed separately on data points from each isotherm to obtain values of each parameter that corresponded to a particular temperature. All three parameters appeared to vary with temperature. The relationships selected to describe the temperature dependence of the Chung-Pfost parameters are given in Table III. The coefficient of determination (R^2) measures the goodness of fit for the models chosen to describe the temperature dependence of Chung-Pfost parameters.

The equations given in Table II were then substituted into the original Chung-Pfost equation (equation 1). The resulting expression gave the moisture content as a nonlinear function of temperature and relative humidity with seven unknown coefficients. The seven unknown coefficients were determined by performing a final nonlinear regression, using all the data points from all four isotherms.

A similar procedure was followed in obtaining the parameters D, K, and N for the Henderson equation:

$$Me = [-\ln(1-rh)/(K(T + D))]^{1/N} \qquad (2)$$

The models chosen to describe the dependence of the Henderson parameters on temperature are given in Table IV.

The results of the regression analysis performed to determine the parameters for the Chung-Pfost and the Henderson equations are presented in Tables V and VI. A comparison between the fitted EMC equations and the observed values of equilibrium moisture are provided in Figs. 1–4. Predicted isotherms are plotted for each of four temperatures investigated.

Fairly good fits of experimental data were obtained for all four equations considered. The use of temperature-dependent parameters did not appear to be justified. Only a small improvement in goodness of fit was obtained at the expense of substantially increasing the complexity of the EMC equations.

All four equations overpredicted equilibrium moisture contents in the middle of the relative humidity range and underpredicted at the low end. This trend was most pronounced in the two equations based on Henderson's equation.

TABLE II
Explanation of Symbols

Parameter	Definition
A	In the Chung-Pfost EMC equation ($J \cdot kg \cdot mole^{-1}$)
B	In the Chung-Pfost equation
C	In the Chung-Pfost equation (°C)
D	In the Henderson EMC equation (°C)
K	In the Henderson equation ($°C^{-1}$)
Me	Dry basis equilibrium moisture content (decimal)
N	In the Henderson equation
rh	Relative humidity (decimal)
T	Temperature (°C)

TABLE III
Models Adopted to Describe the Temperature Dependence of the Chung-Pfost Parameters

Parameter	Model	R^2
A	$A1 + A2 \cdot T$	0.995243
B	$B1 + B2 \cdot T + B3 \cdot T^2$	0.999845
C	$C1 + C2 \cdot T$	0.909559

TABLE IV
Models Adopted to Describe the Temperature Dependence of the Henderson EMC Parameters

Parameter	Model	R^2
D	$D1 + D2 \cdot T$	0.932744
K	$K1 + K2 \cdot T + K3 \cdot T^2$	0.979473
N	$N1 + N2 \cdot T$	0.971344

Comparison with Literature Results

The equilibrium moisture contents measured for white beans were found to be in general agreement with data published for other dry beans. Table VII gives the dry basis equilibrium moisture contents for several types of dry beans taken from the literature (ASAE 1979, Weston and Morris 1954). Also included are dry basis EMC values calculated for white beans, using the Henderson equation with temperature-independent parameters (Table V).

Particularly close agreement in EMC may be observed between the "seafarer" white beans and both the small white flat beans and the dark red kidney beans for intermediate values of relative humidity. Moisture content differed by 1% or less for relative humidities from 30–70%. Direct comparison of the data obtained in this study with EMC data reported in the literature was not possible because conditions of temperature and relative humidity did not coincide.

TABLE V
Estimated Parameters Chung-Pfost Equilibrium Moisture Content Equation

Parameters	Standard Error Moisture
Temperature-independent	
A = 33.1	0.0047
B = 13.73	
C = 60.02	
Temperature-dependent	
$A = -18.52 + 24.4T$	
$B = 14.72 - 0.1278T + 0.002613T^2$	0.0073
$C = -10.68 + 0.652T$	

TABLE VI
Estimated Parameters for Henderson's Equilibrium Moisture Content Equation

Parameters	Standard Error Moisture
Temperature-independent	
D = 87.46	0.0075
K = 0.1633	
N = 1.567	
Temperature-dependent	
$D = 190.6 + 10.63T$	
$K = 0.0885 - 0.00241T + .0000224T^2$	0.0069
$N = 1.803 - 0.00728T$	

TABLE VII
A Comparison of the EMC (% dry basis) of White Beans with That of Other Dry Beans at 25°C

	Relative Humidity (%)						
	20	30	40	50	60	70	80
Soybeans	5.6	6.5	7.4	8.5	10.7	13.8	18.8
Dry beans, flat, small white	8.0	9.1	10.5	12.1	14.4	17.5	22.4
Dry beans, dark red kidney	7.6	8.9	10.5	12.4	14.5	17.6	21.8
Seafarer white (calculated using Henderson equation)	6.0	8.1	10.2	12.3	14.8	17.6	21.1

CONCLUSIONS

The Chung-Pfost and the Henderson equations were comparable in their ability to fit equilibrium moisture content data for white beans. The use of temperature-dependent parameters in either of the above equations did not significantly improve the fit of the experimental data. Use of the simpler, three-constant EMC models, rather than the more complex seven-constant models, is indicated.

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