Dynamic equilibrium moisture content for grain drying

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Chen, C. and Jayas, D.S. 1998. **Dynamic equilibrium moisture content for grain drying.** Can. Agric. Eng. **40**:299-303. For analysis of thin-layer drying data, equilibrium moisture content (EMC) of grains is needed. Two methods to assess equilibrium moisture content values, one based on sorption data (static EMC, Me_s) and the other based on non-linear regression of thin-layer drying data (dynamic EMC, Me_d), were investigated for application to the drying of corn and rough rice. The Me_d values were different from Me_s values in the high and low RH ranges. The fitting of thin-layer drying equations for corn kernels and rough rice was improved by adopting the Me_d parameter. Validation of the Me_d concept on other grains needs to be done and relationships among Me_d and other factors need to be established. **Keywords:** sorption, drying, dehydration, storage, grain.

Pour analyser les données de séchage en couche mince, la teneur en eau des grains à l'équilibre doit être connue (EMC). Deux méthodes pour déterminer la teneur en eau à l'équilibre, une s'appuyant sur des données de sorption (EMC statique, Me_s), et l'autre sur une régression non-linéaire de données de séchage en couche mince (EMC dynamique, Me_s), ont été étudiées pour être utilisées dans le séchage du maïs et du riz brut. Les valeurs de Me_d étaient différentes de celles de Me_s pour des humidités relatives élevées et faibles. On a obtenu un meilleur ajustement des équations de séchage en couche mince pour les grains de maïs et le riz en adoptant le paramètre Me_d. La validation du concept Me_d pour d'autres types de grains doit être faite. On doit aussi établir des relations entre Me_d et d'autres paramètres. **Mots-clés:** sorption, séchage, déshydratation, entreposage, grains.

INTRODUCTION

Drying is an essential unit operation in post harvest handling, storage, and processing of many agricultural products. Thin-layer drying equations of the form of Eq. 1 contribute to the understanding of the heat and mass transfer phenomena for designing and improving drying equipment. The final moisture content of the product that can be reached at particular conditions of the drying air is an important parameter in thin-layer drying models and is known as equilibrium moisture content (Me).

The typical lumped equation for thin-layer drying is:

$$MR = \frac{M(t) - Me}{Mi - Me} = F(t) \tag{1}$$

where:

MR = moisture ratio,
M(t) = moisture content at time(t) (% db),
Mi = initial moisture content (% db),
Me = equilibrium moisture content (% db), and
F(t) = a function of drying time; several forms of F(t) were reviewed by Jayas et al. (1991).

Three different methods to estimate Me values in drying equations have been reported in the literature: (1) equilibrium moisture content (EMC)/equilibrium relative humidity (ERH) equation (Me_s), (2) final moisture content from the drying process (Me_f), and (3) dynamic equilibrium moisture content (Me_d). In the first method, the value of Me_s for the drying equation is calculated from an EMC/ERH model. For example, Ezeike and Otten (1991) first established the EMC/ERH properties of unshelled melon seeds and then used these data to determine Me_s for use in the thin-layer drying equation for this product.

In cases where EMC/ERH data are limited or not available, the final moisture content value from the thin-layer drying test is used to approximate the EMC value. When the drying sample reaches a constant mass for a certain time, the grain is assumed to be in equilibrium and the final moisture content is considered the EMC value. This method was adopted by Syarief (1982) in the study of thin-layer drying rates of sunflower seeds, by Chhinnan (1984) for in-shell pecans, and by Li and Morey (1987) for American ginseng.

In the dynamic equilibrium moisture content method, during analysis of data from the drying process, the Me in Eq. 1 is assumed as a parameter (Me_d), which can be obtained using non-linear regression along with other drying parameters of the drying equations (Jayas et al. 1988; Moreira and Bakker-Arkema 1989; Sun and Woods 1994).

The purpose of this study was to compare the fitting-agreement of the thin-layer drying equation using either Me_s or Me_d and to validate the application of the dynamic EMC (Me_d) concept to the drying process. The relationship between Me_d and drying air conditions was also determined.

MATERIALS and METHODS

Data collection

Thin-layer drying data for corn kernels were used to determine the Me_d properties. The data for the corn were from three sources at various temperature and relative humidity ranges: 32.2-71.1°C, 10-83.2% RH (Troeger 1967); 10.0-43.3°C, 30-90% RH (Misra 1978); and 26.7-93.3°C, 0.3-11.0% RH (Li and Morey 1984). The data for rough rice were at 35-60°C and 10-50% RH (Chen 1996).

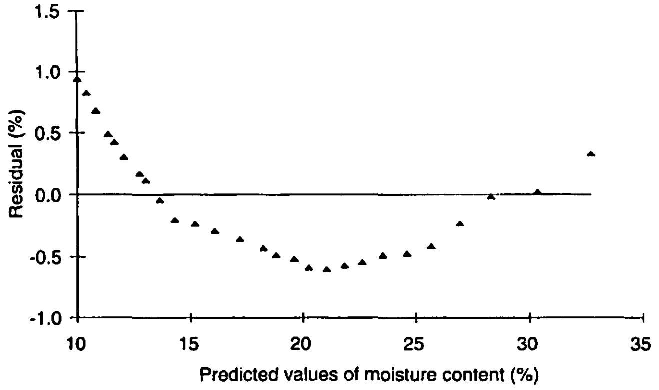

Fig. 1. Residual plots of moisture content for thin-layer drying equation (Eq. 2) of corn kernels when Me_s values calculated from Chen and Morey's (1989b) data were used in the model for drying data of Li and Morey (1984) at 71.1 °C and 1% RH.

Thin-layer drying equation

Corn kernels A thin-layer empirical drying equation, proposed by Page (1949), was used to describe the drying rate of corn kernels:

$$\frac{M(t)-Me}{Mi-Me}=\exp(-Kt^{N}) \quad (2)$$

where K, N = drying parameters.

We calculated the Me_s values (for use in Eq. 2 in place of Me) for the drying data of Troeger (1967) and Misra (1978) using the modified-Henderson equation with the parameters adopted from the desorption data of Rodriguez-Arias (1956). The Me_s values for the drying data of Li and Morey (1984) were computed from the modified-Henderson equation with parameters adopted from Chen and Morey (1989b).

Rough rice Another thin-layer drying equation (Eq. 3) was adopted to quantify the drying characteristic of rough rice (Chen 1996).

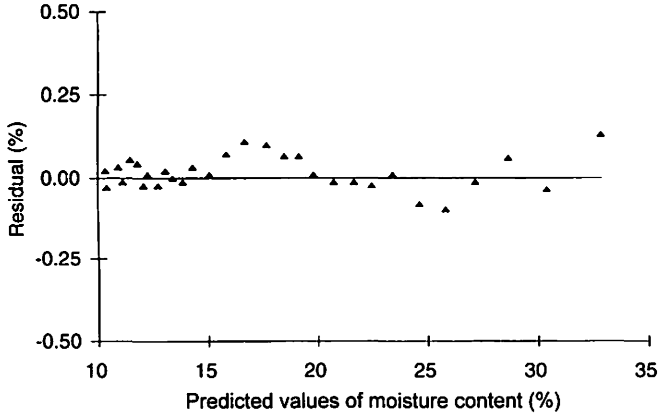

Fig. 2. Residual plots of moisture content for thin-layer drying equation (Eq. 2) of corn kernels when Me_d was used in the model for drying data of Li and Morey (1984) at 71.1 °C and 1% RH.

$$\frac{M(t)-Me}{Mi-Me}=A1\exp(B1\,t)+A2\exp(B2\,t) \quad (3)$$

where A1, A2, B1, B2 = equation parameters.

The Me_s values (for use in Eq. 3 in place of Me) were derived from desorption data for rough rice obtained by Chen and Tsao (1990).

Data analysis

A program, "DEMC", written in QBASIC, was used to estimate the parameters of Eqs. 2 and 3 and associated statistics. Two parameters were estimated for Eq. 2 (K, N) and four parameters for Eq. 3 (A1, A2, B1, B2). To compare the fitting-agreement of the thin-layer drying model with Me_s or Me_d values, Me in Eqs. 2 and 3 was taken as a parameter (Me_d), and determined using nonlinear regression along with their drying parameters.

The criteria for comparison were the standard error of the estimated value (S.E.) and residual plots. If a model correctly explains the observed values of the dependent variable, residuals should be randomly distributed around zero. A systematic pattern in the residuals indicates that the model fails to explain the variation in the data.

RESULTS and DISCUSSION

Comparison of the fitting-agreement of thin-layer drying models

Figures 1 and 2 show the residual plots for Li and Morey's (1984) drying data at 71.1°C and 1.0% RH when Me_s and Me_d, respectively, were used in Eq. 2. When the Me_s value was used in the drying equation, the residual plots showed a clear pattern (Fig. 1). The deviations of moisture content in Fig. 1 were within 1.5%. For the Me_d model (Me replaced by Me_d in Eq. 2), the residual plots were improved and deviations of moisture content were within 0.1% (Fig. 2).

Figures 3 and 4 show the residual plots for Troeger's (1967) data of drying corn at 32.8 °C and 39.5% RH. The results with Me_s in Eq. 2 showed a clear pattern and indicate the large deviation of moisture content from -2.0 to 1.5% (Fig. 3). The residual plots for results of Eq. 2 with Me_d had uniform

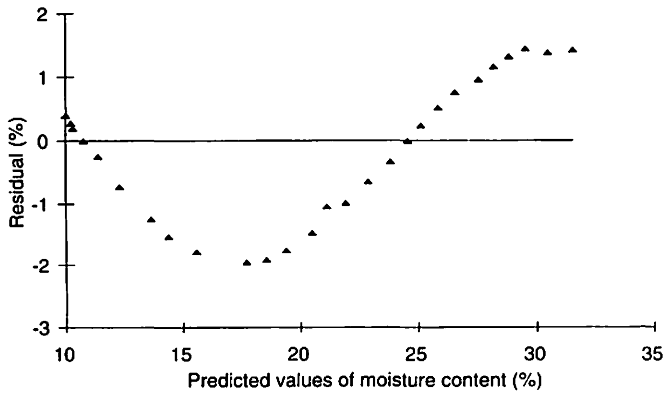

Fig. 3. Residual plots of moisture content for thin-layer drying equation (Eq. 2) of corn kernels when Me_s values calculated from Rodriquez-Arias' (1956) data were used in the model for drying data of Troeger (1967) at 32.8 °C and 39.5% RH.

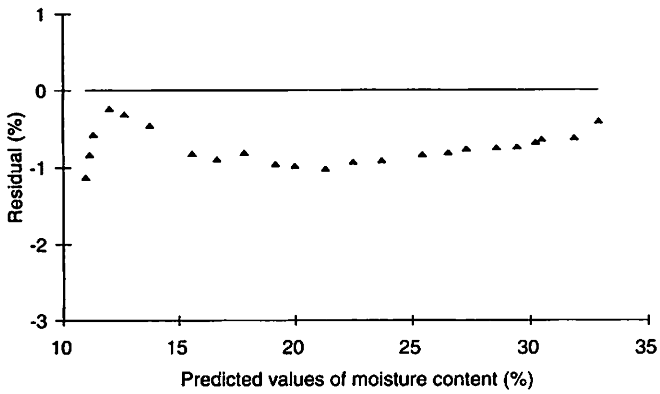

Fig. 4. Residual plots of moisture content for thin-layer drying equation (Eq. 2) of corn kernels when Me_d was used in the model for drying data of Troeger (1967) at 32.8 °C and 39.5% RH.

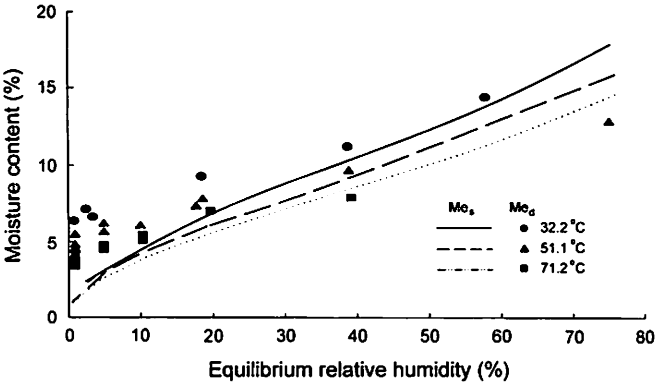

Fig. 5. Comparing the Me_s values calculated from Rodriguez-Arias' (1956) data with Me_d values obtained from drying data of Troeger (1967) for corn kernels.

distribution, however, the residuals were not randomly distributed around zero (Fig. 4). Similar results were obtained for Misra's (1978) data for corn and Chen's (1996) data for rough rice.

Using Me_d as a parameter in the drying equation improved the fitting-agreement for all sets of data, especially for drying air in the low RH range.

Comparison of the Me_d and Me_s values

Corn kernels To compare the Me_d value in the low RH range, two sets of monolayer values (Mo) were calculated by the Brunauer-Emmett-Teller (BET) equation (Brunauer et al. 1938). The technique used to find the monolayer value was adopted from Labuza (1984). The Mo values at each temperature for two sets of desorption data are given in Table I.

We determined the relationships between Mo and temperature for Rodriguez-Arias' (1956) desorption data (Eq. 4) and Chen and Morey's (1989b) data for cultivar 'V.R.' (Eq. 5) as:

$$Mo1 = 0.4931\exp(793.92 / T_k) \tag{4}$$

$$Mo2 = 0.4028\exp(826.65 / T_k) \tag{5}$$

where T_k = temperature (K).

The Me_d values computed from Troeger's (1967) drying data are shown in Fig. 5. In the intermediate RH range (40-60%), the Me_d value approached the Me_s value. In the low RH range (RH < 20%), all Me_d values were higher than Me_s values and close to the monolayer values calculated from Eq. 4.

Table I. Monolayer values for corn kernels as a function of temperature.

	Rodriguez-Arias' (1956) data					
Temperature (°C)	4.5	15.6	30.3	37.8	50.5	60.0
Mo (% db)	8.52	7.74	6.84	6.39	5.76	5.28
	Chen and Morey's (1989b) data					
Temperature (°C)	5	15	25	35	45	
Mo (% db)	7.91	7.10	6.62	5.64	5.57	

Figure 6 shows the Me_d values calculated from Misra's (1978) drying data. At 50% RH, Me_d and Me_s values were close. The Me_d values were smaller than Me_s in the high RH range.

The computed Me_d values obtained from Li and Morey's (1984) data are tabulated in Table II along with Mo values calculated using Eq. 5 and Me_s values for data of Chen and Morey (1989b). All Me_d values were higher than the Me_s values in the low RH environments. Most of the Me_d values were higher than the Mo values (calculated from Eq. 5). The reason might be that the drying period was relatively short (less than 10 h), thus the Me_d value did not reach the monolayer value.

Rough rice The monolayer values of rough rice calculated by the BET equation from the desorption data (Chen and Tsao 1990) were related to temperature as:

$$Mo = 0.0318\exp(1764.6 / T_k) \tag{6}$$

The Me_d values calculated from Chen's (1996) data by Eq. 3 are shown in Figure 7. In the middle RH range (40-50%), the Me_d values approached the Me_s values. At lower RH, the Me_d values were higher than the Me_s values (Fig. 7). The Me_d values were significantly higher than the monolayer values (Fig. 8). The difference between Mo and Me_d values was greater for rough rice than corn (Fig. 5-8). It is possible that drying of rough rice to reach equilibrium is more difficult than of corn.

The physical meaning of dynamic equilibrium moisture content

Based on the above results, a relationship between Me_d, Me_s, and RH could be proposed. In the high RH range, Me_d is smaller than Me_s; in the intermediate RH range, the two values coincide; in the low RH region, Me_d is higher than Me_s and close to the monolayer value. However, no quantitative values could be stated for dividing these three RH ranges.

Table II. Me_d and Me_s data for thin-layer drying data of Li and Morey (1984).

Temperature (°C)	Mo (% db)	RH (%)	Me_d (% db)	Me_s (% db)
26.7	6.37	7.9	10.11	4.34
		9.9	10.16	4.89
		9.9	11.12	4.89
		10.2	10.69	4.94
		10.8	11.11	4.96
48.9	5.27	2.82	9.14	2.75
		2.85	8.99	2.77
		2.86	9.38	2.77
		2.88	8.43	2.78
		3.02	8.47	2.85
		3.43	7.34	3.04
		4.65	5.86	3.55
71.1	4.46	0.01	6.17	0.01
		1.01	7.41	1.50
		1.05	5.66	1.51
		1.27	5.86	1.66
93.3	3.86	0.46	4.98	0.92
		0.40	4.90	0.86
		0.40	4.27	0.86
		0.35	4.92	0.80
		0.30	4.31	0.75

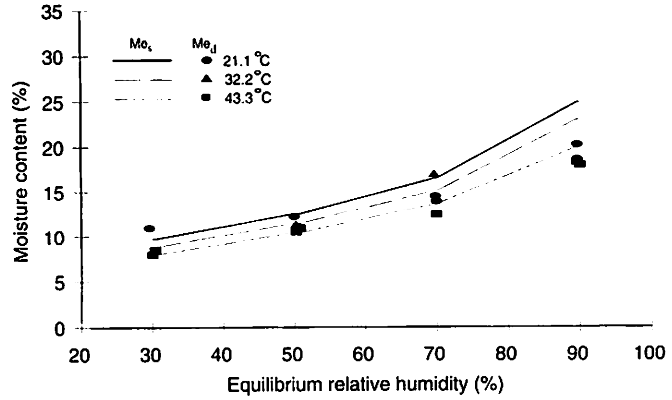

Fig. 6. Comparing the Me_s values calculated from Rodriguez-Arias' (1956) data with Me_d values obtained from drying data of Misra (1978) for corn kernels.

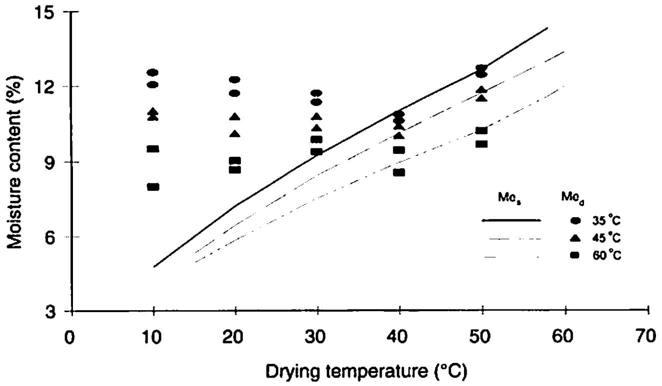

Fig. 7. Comparing the Me_s values calculated from Chen and Tsao's (1990) data with Me_d values obtained from drying data of Chen (1996) for rough rice.

Many theoretical and empirical drying equations assume the moisture content of the grain's surface to be equal to the equilibrium moisture content and the equilibrium state to occur instantaneously. These assumptions are valid only in the intermediate RH region.

When grains with high initial moisture content begin to dry, the ambient RH value is lower than its ERH value, so the surface's ERH (superficial ERH), is lower than the ERH in the interior of the grain. Gradients in ERH and moisture exist at this stage, thus the Me_d (the surface moisture content) is lower than the Me_s value. This concept is similar to that of Roth and Loncin (1981). The existence of the difference between the values of Me_d and Me_s was also implied by the work of Brooker et al. (1974). These investigators mentioned that the grain surface moisture would not come to equilibrium immediately at the beginning of the drying process since the convective mass-transfer coefficient was finite and would come to equilibrium exponentially.

In the low RH region, the high heat of desorption for the grain at low moisture content restrains the movement of the water vapour. The moisture content of the grain cannot come to equilibrium with the drying air within the short drying period.

Brooker et al. (1974) mentioned that one of the main sources of error between simulated and experimental drying results was insufficient precision of the EMC equations for grain at relative humidities above 90%. The errors for thin-layer drying equations in the high RH range may not only be caused by the inaccuracy of the EMC value, but also by the inadequate concept of the EMC value used to represent the surface moisture content of the grain.

The relationship among Me_d and other factors (grain and drying air properties) needs to be studied in more detail. However, as far as drying simulation is concerned, replacing the conventional EMC model by an empirical Me_d equation is sufficient from an engineering standpoint. For example, the relationship between Me_d value and drying air properties for data of Troeger (1967) was calculated by regression analysis as:

$$Me_d = (15.83 - 0.1063T)\left(\frac{RH}{1-RH}\right)^{0.221} \quad \text{S.E.} = 0.508\% \tag{7}$$

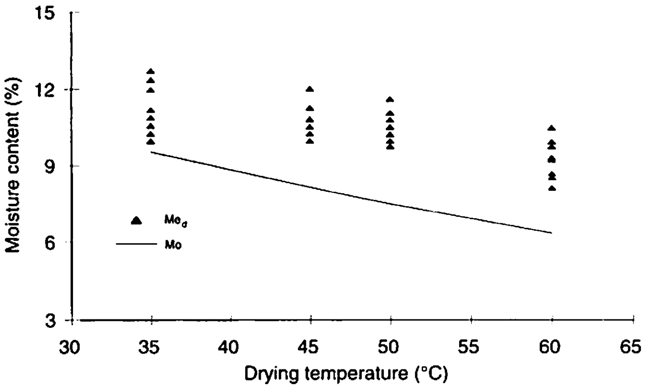

Fig. 8. Comparing the Me_d values from drying data of Chen (1996) with monolayer values.

$$Me_d = 9.5151 - 0.0767T + 10.265RH + 0.1963\ln(RH)$$

$$\text{S.E.} = 0.518\% \qquad (8)$$

where

T = temperature (°C), and

RH = relative humidity (fraction).

Equation 7 is similar in form to the Modified-Oswin (Chen and Morey 1989a) equation and Eq. 8 is a multiple regression equation. Both equations had residual plots of uniformly scattered data points and residual values of moisture content were less than 1%.

CONCLUSIONS

The equilibrium moisture models have been widely applied to calculate the Me_s value for thin-layer drying equations for many years. The EMC-ERH data are difficult to measure at the high temperatures at which drying experiments are conducted. Many thin-layer drying techniques have been developed and could be used to obtain accurate data. From the drying results and nonlinear regression analysis, Me_d values could be obtained easily. Then the relationship between Me_d, drying air, and grain properties could be established. This provides a direct and accurate method for obtaining adequate Me_d values for drying simulation.

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