Comparison and Selection of EMC/ERH Isotherm Equations for Drying and Storage of Grain and Oilseed

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ABSTRACT

Wheat, shelled corn and rice are the most popular grown cereal grains and rapeseed (canola) is the most popular grown oilseed in the world. Thorough literature surveys reveal that a large number of publications contain EMC/ERH data for these grains and oilseed. From these publications, experimental data points are extracted, forming data sub-sets suitable for evaluating the isotherm equations. Moreover, these data points also form merged data sets that can be used for various applications. Some commonly used EMC/ERH equations are compared based on their ability to fit these data sub-sets, and the most appropriate equations are selected to fit the merged data sets that describe adsorption, desorption and average isotherms for the grains and oilseed. The best fitted equations provide a sound basis for future work on the drying and storage of wheat, shelled corn, rice and rapeseed.

Keywords: Canola, Corn, Desorption, Drying, EMC, Equilibrium moisture content, Equilibrium relative humidity, ERH, Maize, Rapeseed, Rice, Storage, Wheat

INTRODUCTION

The most popular grown cereal grain and oilseed in the world are wheat, shelled corn and rice, and rapeseed (canola), respectively. Immediately after harvest, they are normally dried to the moisture content level at which there is no danger of growth of undesirable micro-organisms. Then, they are stored for a considerable period of time in a bio-deterioration-controlled environment, which is accomplished by controlling the moisture content and temperature. Along with the intrinsic drying kinetics, in order to describe the drying process and its effect on water activity, which controls the biological change in storage, a sound knowledge of the relationship between equilibrium moisture content (EMC) and equilibrium relative humidity (ERH) is essential (Sun and Woods, 1996; 1997; 1998). This relationship is described by the EMC/ERH sorption isotherm equations.

More than 200 EMC/ERH equations are available, however no single equation has the ability to describe accurately the EMC/ERH relationships for various grains over a broad range of relative humidity and temperature (Van den Berg and Bruin, 1981; Sun and Woods, 1993). Therefore, for a specific crop, there is a need to search for the most appropriate EMC/ERH equation (Sun and Woods, 1994c; Sun and Byrne, 1998; Sun, 1998; 1999). During recent years, the author has consistently conducted research in this area, which covers typical grains, *i.e.*, wheat (Sun and Woods, 1994c), shelled corn (Sun, 1998) and rice (Sun, 1999) and typical oilseed, *i.e.*, rapeseed (Sun and Byrne, 1998). This paper summarises the research results.

MATERIALS AND METHODS

Common Used EMC/ERH Equations

Various literature surveys show that the following equations are commonly used to describe the EMC/ERH sorption behaviour of grain and oilseed (Pfost *et al*., 1976; Boquet *et al*, 1979; Chen and Morey, 1989; Sun and Woods, 1994c; ASAE, 1997; Sun and Byrne, 1998; Sun, 1998; 1999). The following symbols are used in describing the equations: *r.h.* = relative humidity (water activity), decimal; *M* = moisture content, percentage dry basis; *T* = temperature, ^{o}C; T_K = absolute temperature, K; P_s = saturated water vapour pressure, Pa; and C_1, C_2, C_3 and C_4 = coefficients in equations.

1. Chen-Clayton Equation (CHCE):

$$r.h. = \exp\left[-\frac{C_1}{T_K^{\,C_2}}\exp\left(-C_3 T_K^{\,C_4} M\right)\right] \quad (1)$$

2. Modified-Chung-Pfost Equation (MCPE):

$$r.h. = \exp\left[-\frac{C_1}{T + C_2}\exp\left(-C_3 M\right)\right] \quad (2)$$

3. Modified-Halsey Equation (MHAE):

$$r.h. = \exp\left(-\exp\left(C_1 + C_2 T\right) M^{-C_3}\right) \quad (3)$$

4. Modified-Henderson Equation (MHEE):

$$r.h. = 1 - \exp\left[-C_1\left(T + C_2\right) M^{C_3}\right] \quad (4)$$

5. Modified-Oswin Equation (MOSE):

$$r.h. = \frac{1}{1 + \left(\frac{C_1 + C_2 T}{M}\right)^{C_3}} \quad (5)$$

6. Strohman-Yoerger Equation (STYE):

$$r.h. = \exp\left[C_1 \exp(-C_2 M)\ln P_s - C_3 \exp(-C_4 M)\right] \quad (6)$$

EMC/ERH Sorption Data

In order to identify the most appropriate equation to describe the EMC/ERH isotherm for a specific crop, a large number of EMC/ERH sorption data are needed. Extensive literature surveys reveal that many researchers have measured the EMC/ERH data for grain and oilseed. Table 1 shows the results of these surveys.

All the data points listed in Table 1 are original experimental points either cited directly from tables or read (digitised) from experimental points on figures in the identified publications. The total data sets in Table 1 is the combination of both adsorption and desorption data sets.

Comparison of EMC/ERH Equations

In order to compare the performance of the EMC/ERH equations, the effects of the uncertainties in crop varieties, sorption processes, experimental techniques and procedures in the data sources should be minimised. Many publications listed in Table 1 contain EMC/ERH data sources over a range of temperature. According to the crop variety and the sorption process in the experiment, the data source can be used to generate data sub-sets, each of which gives a single variety and a single sorption process.

Using the commercial statistics software packages, the common used EMC/ERH equations are used to fit these data sub-sets. The fitting is a non-linear regression process and the regression results include the best-fitted coefficients for the equations and three error parameters, *i.e*., the residual sum-of-squares (RSS), the standard error of estimate (SEE) and the mean relative derivation (MRD). Table 2 gives the details of the EMC/ERH equations and the number of data sub-sets used for fitting.

The comparison of the EMC/ERH equations is based on the three error parameters: RSS, SEE and MRD. Two comparing methods are used. In the first, the average values of the three error parameters over all the data sub-sets and equations-fitted are calculated. In the second method, the number of times an equation best fits a data sub-set is counted. This comparison results in the identification of the most appropriate equation, which is then used to fit the large data sets given in Table 1.

RESULTS AND DISCUSSION

Selection of EMC/ERH Equation

The selection of the most appropriate equation for a specific crop is based on the two comparison methods described previously. Tables 3 and 4 show the comparing results.

Tables 3 and 4 show that for wheat, the MCPE and STYE give comparative performance, which is better than the other equations. Given the fact that the MCPE is a three-coefficient equation while STYE is a four-coefficient equation, the MCPE is identified as the most appropriate equation for wheat. The comparison also clearly shows that the MOSE, STYE and MHAE are the most appropriate equations for shelled corn, rice and rapeseed, respectively. The MHEE is among the least successful equation for all the crops.

The results in Tables 3 and 4 confirm that for a specific crop, there exists an appropriate equation that best describes its EMC/ERH sorption behaviour. No single equation exhibits the ability to describe accurately the EMC/ERH relationships for all grains over a broad range of relative humidity and temperature (Sun and Woods, 1993).

Fitted Equations for Drying and Storage

The identified equations are used to fit the merged data sets describing adsorption and desorption processes. They are also used to fit the total data set describing the average curves. Table 5 lists the best-fitted coefficients for the most appropriate equations.

The fitted equations for adsorption and desorption listed in Table 5 can be used for describing rewetting and drying processes. In addition to the drying process, which requires the use of the desorption isotherm equation, the rewetting process does occur during storage, especially in the region near the ventilation inlet (Sun and Woods, 1996; 1997; 1998). Therefore, description of the water activity during adsorption is needed to accurately control the moisture content level in this region. The equation describing the average curve can be used in general applications.

CONCLUSIONS

The Modified-Chung-Pfost equation, Modified-Oswin equation, Strohman-Yoerger equation and Modified-Halsey equation are identified as the most appropriate equations for describing the EMC/ERH sorption isotherms for wheat, shelled corn, rice and rapeseed, respectively.

No single equation has the ability to describe accurately the EMC/ERH relationships for all crops over a broad range of relative humidity and temperature.

The Modified-Henderson equation is among the least successful equations for wheat, shelled-corn, rice and rapeseed.

Equations fitted to large data sets from different sources minimise the effects of crop varieties, measuring techniques, and are more accurate. Therefore, the equations fitted to the adsorption, desorption and total data sets provide a sound basis for future work on drying and storage of grain and oilseed.

The techniques may be useful for examining EMC/ERH data for other grains, particularly where a large data set is available.

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Table 1. Literature sources giving EMC/ERH experimental data.

Crop	Number of Publications	Number of Data Points		
		Total	Adsorption	Desorption
Wheat	33	1109	387	722
Shelled Corn	20	591	127	464
Rice	18	763	200	563
Rapeseed	12	668	291	377

Table 2. EMC/ERH equations and data sub-sets.

Crop	Number of Data Sub-Sets	Common Equations Used in Fitting					
		CHCE	MCPE	MHAE	MHEE	MOSE	STYE
Wheat	29	✓	✓		✓	✓	✓
Shelled Corn	19		✓		✓	✓	
Rice	18		✓		✓	✓	✓
Rapeseed	21		✓	✓	✓	✓	

Table 3. Average values over all the data sub-sets of the three error parameters.

Crop	Equation	RSS	SEE	MRD
Wheat	CHCE	0.0119	0.0232	0.04112
	MCPE	0.0072	0.0187	0.03327
	MHEE	0.0139	0.0255	0.04463
	MOSE	0.0095	0.0201	0.03990
	STYE	0.0062	0.0183	0.02928
Shelled Corn	MCPE	0.0187	0.0240	0.04038
	MHEE	0.0211	0.0291	0.05202
	MOSE	0.0195	0.0237	0.04237
Rice	MCPE	0.0182	0.0217	0.03942
	MHEE	0.0199	0.0226	0.03869
	MOSE	0.0206	0.0250	0.04668
	STYE	0.0123	0.0180	0.03071
Rapeseed	MCPE	0.0543	0.0576	0.07770
	MHAE	0.0250	0.0265	0.04474
	MHEE	0.0566	0.0481	0.08372
	MOSE	0.0298	0.0299	0.04903

Table 4. Number of fits producing the minimum error values for each equation.

Crop	Equation	RSS	SEE	MRD
Wheat	CHCE	2	1	2
	MCPE	5	12	2
	MHEE	1	1	3
	MOSE	10	9	7
	STYE	16	6	15
Shelled Corn	MCPE	7	7	8
	MHEE	3	3	5
	MOSE	9	9	6
Rice	MCPE	1	2	0
	MHEE	4	4	3
	MOSE	2	2	4
	STYE	10	9	11
Rapeseed	MCPE	0	0	0
	MHAE	17	17	14
	MHEE	0	0	0
	MOSE	4	4	7

Table 5. The best fitted coefficients for adsorptive, desorptive and average isotherm equations.

Data Sets	Best Fitted Equation Coefficients				RSS	SEE	MRD
	C_1	C_2	C_3	C_4			
Wheat: Modified-Chung-Pfost Equation							
Adsorption	401.52	73.607	0.14974		1.1950	0.0558	0.16423
Desorption	545.25	64.047	0.17316		2.7264	0.0669	0.59591
Total	478.87	64.933	0.16558		4.8434	0.0662	0.55857
Shelled Corn: Modified-Oswin Equation							
Adsorption	13.1882	-0.058628	2.98726		0.19965	0.04013	0.06152
Desorption	13.9005	-0.076819	2.96243		1.71130	0.06093	0.10346
Total	13.7738	-0.074127	2.96856		1.93735	0.05740	0.09660
Rice: Strohman-Yoerger Equation							
Adsorption	2.60693	0.22350	8.48875	0.19608	0.83505	0.06527	0.10577
Desorption	1.03151	0.13755	7.73688	0.17268	2.77199	0.07042	0.12657
Total	1.15668	0.15345	7.78269	0.17828	4.17767	0.07419	0.13202
Rapeseed: Modified-Halsey Equation							

Adsorption	2.7812	$-8.9162x10^{-4}$	1.6685	0.86939	0.05477	0.09866
Desorption	2.8989	$-1.4596x10^{-2}$	1.5454	3.10511	0.09112	0.17269
Total	2.8380	$-9.6915x10^{-3}$	1.5845	4.38937	0.08124	0.14770