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Study of Adsorption and Desorption Equilibrium Relationships for Yellow Dent, White, and Waxy Corn Types Using the Modified Chung-Pfost Equation

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STUDY OF ADSORPTION AND DESORPTION EQUILIBRIUM RELATIONSHIPS FOR YELLOW DENT, WHITE, AND WAXY CORN TYPES USING THE MODIFIED CHUNG-PFOST EQUATION

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ABSTRACT. *Three different corn types (yellow dent, waxy, and white) harvested in the fall of 2003 were used to run a set of desorption and adsorption EMC/ERH experiments. The range of temperature and moisture content (MC) were designed to cover the typical operating conditions for natural air / low-temperature in-bin drying systems in the Midwest during the fall (0°C to 25°C and 12% to 20% for temperature and MC, respectively). Standard deviations of the experimental data ranged from 0.00°C to 0.58°C, 0.00% to 0.52% for EMC values, and 0.01% to 4.36% for ERH values. Non-linear regression analysis was used to determine the best adsorption and desorption parameters for the modified Chung-Pfost equation for each corn type. A second adsorption and desorption EMC/ERH experiment was carried out with samples of yellow dent and white corn harvested during the 2004 drying season. The modified Chung-Pfost equation using the 2003 set of parameters was validated with the 2004 EMC/ERH data. The MRD and SE for the three corn types ranged from 1.9 to 2.6 and 1.6 to 1.9 compared to 4.3 and 5.0, respectively, reported for the ASAE Standard data. The main conclusions of this study were that the different corn types investigated had different EMC/ERH relationships, the adsorption and desorption relationships were different for each corn type, and the prediction of EMC/ERH values during desorption using the current ASAE Standard set of parameters available only for yellow corn was substantially different compared to the yellow dent, white, and waxy corn EMC/ERH data reported in this research.*

Keywords. *Adsorption, Chung-Pfost equation, Desorption, Equilibrium moisture content, Equilibrium relative humidity, Waxy corn, White corn, Yellow dent corn.*

The equilibrium moisture content (EMC) determines the moisture content (MC) to which grain can be dried or conditioned under particular psychrometric conditions of the air. This relationship is of critical importance for grain drying and conditioning studies. The equilibrium relative humidity (ERH) determines the maximum interstitial air vapor pressure that can be reached given a certain MC of the stored grain, which is of critical importance for maintaining grain quality.

Several models have been developed to describe the relationship between the EMC or ERH and temperature of grains and oilseeds. In general, these models can be classified as theoretical and semi-theoretical or empirical. Theoretical models are not extensively used to determine moisture equilibrium relationships of agricultural products. This is either because of the lack of accuracy of the EMC theoretical model or because of the lack of product constant values (Brooker et al., 1992).

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Empirical models predict the grain MC based on a set of constants and the temperature and relative humidity of the air. Empirical models are the most frequently used EMC models to determine moisture relationships of agricultural products. According to ASAE Standard D245.5, the most commonly used empirical EMC models for agricultural products are the modified Chung-Pfost, the modified Henderson, the modified Oswin, and the modified Halsey equations (*ASAE Standards*, 2001).

Several studies have been done in the past in order to determine which EMC model is the best. Chen and Morey (1989a) analyzed the prediction of four isotherm equations and different types of grains. The modified Henderson and modified Chung-Pfost equations were good models for starchy grains and fibrous materials. The modified Halsey equation was a good model for high oil and protein products (beans, peanut pod, peanut kernels, rapeseed, soybeans, and sunflower seeds). The modified Oswin equation was a good model for popcorn, corn cobs, whole pods of peanuts, and some varieties of corn. They concluded that no ERH/EMC equation could claim to be the "universal" model. Sun (1998, 1999) gathered experimental EMC/ERH data points from the literature, formed data subsets suitable for evaluating a range of isotherm equations, and arrived at the same conclusion. Bartosik (2003) reviewed the EMC models and concluded that the modified Chung-Pfost equation was the best EMC model for shelled corn.

ASAE Standard D245.5 currently provides a set of three parameter values for the modified Chung-Pfost equation for different agricultural products, including shelled corn. However, the ability of these ASAE Standard parameters to accurately predict EMC/ERH relationships for different corn types and hybrids was questioned (Sun, 1998). According to Neuber (1980), the following factors are a source of variation in the EMC/ERH relationships between different grains, and between different varieties of the same grain type: (1) composition of the materials (e.g., oil, ash, fiber, protein, starch); (2) characteristics of the materials (e.g., variety and size); (3) treatment of samples (e.g., drying temperature, drying method, and rewetting methods); (4) method used to determine MC and RH; (5) method of equilibration; and (6) method of controlling the RH and temperature during the experiment. Rao and Pfost (1980) attempted to capture the effect of some of these factors in an EMC/ERH prediction model. This model predicted the EMC relationship for a given type of grain using its typical protein, oil, and non-fiber carbohydrate contents. Even though there are significant differences in composition among corn types and hybrids and these differences may be responsible for some of the observed variations in the EMC/ERH relationships among different corn types and hybrids, these effects have not yet been captured in a reliable EMC model.

Sun (1998) proposed that the effect of varieties, measuring techniques, and accuracy of the overall experimental procedure on the determination of EMC parameters could be minimized by fitting the equation to large datasets from different sources collected from the literature (19 data subsets). He hypothesized that a set of parameters obtained from a large data set, including different corn varieties, would represent a sort of "universal" set of parameters, useful for a wide range of different grain varieties. The use of a "universal" set of parameters would be useful for some applications in which an estimate of the EMC/ERH relationship of the shelled corn is sufficient. However, it would not be suitable, for instance, for modeling the drying process. Likewise, in-bin drying fan and burner controllers based on EMC models require more accurate EMC/ERH relationships than those obtained by fitting a large data set of different corn types and hybrids, or those obtained based on a single corn hybrid that is no longer commercially available.

Grain composition was identified as one of the main factors affecting EMC relationships (Neuber, 1980). On the other hand, different corn types have different typical composition values (protein, starch, and oil). Thus, an alternative approach to finding a universal set of parameter values for the EMC model is to determine a reliable set of EMC parameter values for each different corn type. It would be expected that a yellow dent corn set of parameters represent the EMC/ERH relationship of the entire group of yellow dent corn hybrids more accurately than white or waxy corn hybrids.

Another limitation of the ASAE Standard is the lack of a set of EMC adsorption parameters. Chung and Pfost (1967a) reported that adsorption and desorption corn isotherms differ. In the range of 20% to 60% RH, the difference (hysteresis) can reach one percentage point of moisture. During natural air / low-temperature (NA/LT) in-bin drying, corn is exposed to a series of drying and rewetting cycles. Chung and Pfost (1967b) showed that repeated drying and wetting cycles tend to reduce the hysteresis effect, but this observation could not be quantified nor modeled. Thus, to accurately predict MC change in the different corn layers, it is important to have reliable adsorption EMC/ERH relationships.

The main goals of this research were: (1) to study the adsorption and desorption equilibrium relationships of three different corn types (yellow dent, white, and waxy), and (2) to obtain the parameters for the modified Chung-Pfost equation that provided the best fit to the data. The study of the EMC relationship focused on common NA/LT in-bin drying operating conditions (i.e., temperature range from 0°C to 25°C and MC range from 12% to 20%).

Methodology

Modified Chung-Pfost Model

The Chung-Pfost equation (a two-parameter equation) was originally developed by Chung and Pfost (1967a). In order to obtain a better fit, Pfost et al. (1976) added a third parameter to take into account the effect of temperature on the other constants, which resulted in the so-called modified Chung-Pfost equation:

$$\mathrm{RH} = \exp\left[-\frac{A}{T+C} * \exp(-B * MC_D)\right] \qquad (1)$$

where RH is the relative humidity (decimal), T is the temperature (°C), MC_D is the moisture content (% d.b.), and A, B, and C are product constants.

Corn Types and Sample Processing

During the fall of 2003, samples of yellow dent, white, and waxy corn were collected. The yellow dent hybrid was Asgrow 740, which was grown in West Lafayette (west-central Indiana). Corn ears of this crop were hand-harvested at MCs ranging from 22% to 24% and hand-shelled. The white corn samples were grown in Princeton (southwestern Indiana). Ears were hand-harvested at MCs from 22% to 23% and subsequently hand-shelled. The white corn samples were composite samples from three different hybrids: Mycogen 6621, Mycogen 761, and Pioneer 32T78. The waxy corn samples were grown in Shelbyville (central Indiana). They were mechanically harvested and shelled with a combine at MCs from 21% to 23%. The waxy corn samples used in this study were composite samples from three different hybrids: Beck 5166wx, Beck 5275wx, and Beck 5322wx. Table 1 shows the grain composition (oil, protein, and starch) for the 2003 corn samples determined with a NIRT analyzer (Infratec 1229, Foss North America, Eden Prairie, Minn.).

During the 2004 drying season, samples of yellow dent and white corn were collected. The yellow dent corn hybrid was Asgrow 740 (same as the 2003 drying season), and it was grown in West Lafayette. The corn was mechanically harvested and shelled with a combine at MCs from 19% to 20%. The white corn samples were grown in Princeton. The samples of white corn were composite samples of Pioneer 32T78 and Agrigold 6537W. The corn was mechanically harvested and shelled with a combine at MCs from 20.7% to 21.5%.

Table 1. Composition of the corn samples used for the EMC/ERH experiments and harvested during the fall of 2003. Values in table are expressed on a 15% moisture content wet basis.

Corn Type	Oil (%)	Protein (%)	Starch (%)
Yellow dent	4.5	8.2	72.4
White	4.4	8.2	72.4
Waxy	3.8	8.0	73.3

Immediately after the corn was harvested and shelled, it was stored in sealed plastic bags in a freezer at temperatures of –16°C for a time period of about 8 months until the EMC/ERH experiment was conducted. The EMC/ERH experiment for the 2003 samples was conducted in June-July 2004, and the EMC/ERH experiment for the 2004 samples was conducted in June-July 2005. Before starting the EMC/ERH experiments, corn samples were thawed, cleaned, and conditioned to different moisture contents.

Mechanically harvested corn might have a slightly higher percentage of mechanically damaged kernels than hand-harvested and shelled corn samples. The effect of damaged kernels in the EMC relationship was not documented in the past. However, for this research, it was considered important to minimize the effect of harvest method on the EMC relationships by thoroughly conditioning and cleaning the corn samples. The cleaning consisted of screening the corn samples using the standard 4.76 mm round-hole sieve for corn. This eliminated most of the fine material and foreign matter of the sample. The remaining damaged and broken kernels were eliminated by visual inspection of the grain. After the cleaning procedure was completed, the corn samples (both hand-harvested and shelled, and mechanically harvested and shelled) were visually free of fine material, foreign matter, broken kernels, and damaged kernels. Half of the samples of each corn type (approx. 5 kg of each) were put in plastic mesh bags and dried by exposure to laboratory ambient conditions (no forced air) to 10% to 11% MC. The dried corn samples were returned to the freezer at –16°C, to be used later for the adsorption EMC/ERH experiments.

The other half of the corn samples were used for the desorption EMC/ERH experiment. The initial wet sample of each of the corn types was divided into a set of five subsamples and placed in mesh plastic bags. The corn subsamples were exposed to laboratory ambient conditions to dry the corn from the initial MC of 21% to 23% to approximately 20%, 18%, 16%, 14%, and 12% MC. During this period, the MCs of the corn samples were closely monitored with a GAC 2100 moisture analyzer (DickeyJohn, Auburn, Ill.). When the corn samples reached the desired final MC, they were transferred from the plastic mesh bags into sealed plastic bags and stored in the freezer for 14 days at –16°C to equilibrate the MC among the individual grain kernels. Three replicates of the moisture equilibrated corn samples were placed in the oven for 72 h at 103°C (±1°C), and MC was determined with the gravimetric method proposed by ASAE Standard S352.2 (*ASAE Standards*, 2003).

The conditioning of the grain samples for the adsorption experiment was carried out by computing first the amount of water required to increase the MC of each of the overdried subsamples (initial MC ranging from 10% to 12%) to the desired final MC of 12%, 14%, 16%, 18%, and 20%. The corn subsamples were rewetted to the desired final MC by mixing in the previously determined amount of distilled water. The re-moisturized corn samples were placed in sealed plastic bags, stored in a refrigerator for 10 days (4°C), and then transferred to the freezer at –16°C for one month to allow for the grain moisture to equilibrate. The MC of equilibrated corn samples for the adsorption EMC/ERH experiment was then determined with the oven method as described above.

Experimental Procedure to Determine the EMC/ERH Relationship of Corn

The experimental procedure followed to determine the EMC relationships of the corn samples was adapted from the procedure described by Chen and Morey (1989b). Approximately 200 g of corn were placed in a plastic container and hermetically sealed with a rubber cap. A factory-calibrated temperature and relative humidity sensor (HMP2030 Series, Vaisala, Inc., Woburn, Mass.) was previously inserted through the rubber cap into the grain to accurately measure the temperature and relative humidity of the interstitial air of the grain. The sensor was connected to a data logger (2625A Hydra Data Logger, Fluke Corp., Everett, Wash.), which recorded interstitial air conditions every 5 min. The sealed containers, with the grain sample and the temperature and relative humidity sensor, were placed in a temperature chamber. This temperature chamber was able to maintain a relatively constant temperature during the entire experiment (±0.5°C). Soon after the grain in the sealed container was placed in the temperature chamber, the grain sample started to equilibrate with respect to the temperature of the chamber. At the same time, the interstitial air started to equilibrate with the temperature and MC of the corn sample. Eventually, the grain sample in the sealed container reached thermo and hygroscopic equilibrium with the confined interstitial air. Thus, the measured temperature and relative humidity were considered the equilibrium temperature and equilibrium relative humidity of the corn sample for that particular grain temperature and MC combination. After the equilibrium condition was reached and recorded, the temperature in the chamber was increased to determine the next isotherm equilibrium condition of the same grain sample.

It was consistently observed that after 3 h of exposing the grain sample in the sealed container to the same temperature, the temperature and relative humidity of the interstitial air did not change further (Bartosik, 2005). Thus, the corn samples were allowed to stabilize for at least 3 h before the equilibrium temperature and ERH conditions were recorded.

Three replicates of each EMC/ERH experiment were conducted for each MC (12%, 14%, 16%, 18%, and 20%), corn type (yellow dent, white, and waxy), and sorption equilibrium condition (adsorption and desorption). The experiment started by placing the corn samples in the temperature chamber at 0°C. After about 3 h, the equilibrium temperature and relative humidity were recorded, and the temperature of the chamber was increased to 5°C. The same procedure was followed to determine the EMC/ERH relationship for 5°C, 10°C, 15°C, 20°C, and 25°C. For the 2004 experiment, the samples were exposed to an additional temperature of 30°C.

Statistical Analysis of the EMC/ERH Data

Before the EMC/ERH experiment with the 2003 corn samples started, the temperature and relative humidity sensors were sent to the factory for service and calibration. Statistical analysis was performed with the SAS software package (SAS 9.0, SAS Institute, Inc., Cary, N.C.). The modified Chung-Pfost equation was programmed into SAS, and the A, B, and C adsorption and desorption parameters for each of the three corn types from the 2003 harvest season were estimated using the n-lin procedure (used to fit non-linear models). The EMC/ERH model used to estimate the parameters for the modified Chung-Pfost equation was constructed as follows:

$$\text{ERH} = CornType + Sorption + MC + Temperature + CornType * Sorption \quad (2)$$

The fit of the three estimated parameters of the modified Chung-Pfost equation corresponding to the three corn types was evaluated. The three standard quantitative methods most often used for comparing different EMC/ERH models are mean relative deviation (MRD), standard error of the estimated value (SE), and the residual sum of squares (RSS) (Chen and Morey, 1989a; Sun, 1999; Sun and Woods, 1994; Chen, 2000; and Chen and Jayas, 1998).

The residual sum of squares was calculated as:

$$\text{RSS} = \Sigma(Y - Y')^2 \quad (3)$$

where Y is the measured value, and Y' is the value predicted by the model.

The mean relative deviation was calculated as:

$$\text{MRD} = \frac{100}{N} * \sum \frac{|Y - Y'|}{Y} \quad (4)$$

where Y and Y' are defined as in equation 3, and N is the number of data points.

The standard error of the estimated value was calculated as:

$$\text{SE} = \sqrt{\frac{\sum (Y - Y')^2}{df}} \quad (5)$$

where Y and Y' are defined as in equation 3, and df is the degrees of freedom of the model.

The EMC/ERH data from the yellow dent and white corn collected during the 2004 drying season were used to validate the estimated parameters for the modified Chung-Pfost equation. The observed EMC/ERH data (samples from 2004) were compared to the predicted data. The prediction was quantified by computing the SE and the MRD.

Results and Discussion

EMC/ERH Experimental Data from the 2003 and 2004 Corn Samples

Tables 2 and 3 summarize the EMC/ERH data for the desorption and adsorption experiments, respectively, for the 2003 corn samples. Tables 4 and 5 summarize the EMC/ERH data for the desorption and adsorption experiments, respectively, for the 2004 corn samples.

Table 6 shows the range of standard deviation values for temperature, moisture content, and relative humidity of the experimental data presented in tables 2 through 5. Across all experiments, the standard deviation values for temperature ranged from 0.00°C to 0.58°C, from 0.00% to 0.52% for the EMC values, and from 0.01% to 4.36% for the ERH values. The variability of the ERH values across the different corn types was similar for both years, although the data from the second year had lower variability than those of the first year.

Table 2. Equilibrium temperature, equilibrium relative humidity, and equilibrium moisture content data for the desorption experiments (2003 corn samples) for the yellow dent, white, and waxy corn types (average of three replicates).

Yellow Dent			White			Waxy		
Temp. (°C)	ERH (%)	EMC (% w.b.)	Temp. (°C)	ERH (%)	EMC (% w.b.)	Temp. (°C)	ERH (%)	EMC (% w.b.)
0.5	29.9	10.0	0.1	44.3	11.3	0.5	32.8	9.6
0.2	62.9	14.6	−0.1	58.4	13.3	0.2	62.8	14.3
0.1	72.9	16.2	0.0	73.9	16.2	0.3	72.2	16.1
0.2	81.1	18.0	0.2	80.0	17.5	0.4	79.0	17.8
0.3	85.7	19.6	0.2	84.9	19.0	0.2	82.6	19.4
5.3	31.8	10.0	5.0	46.8	11.3	4.9	35.7	9.6
5.0	64.6	14.6	4.7	60.4	13.3	4.7	64.0	14.3
4.9	74.0	16.2	4.8	75.0	16.2	4.7	73.7	16.1
5.0	81.7	18.0	4.9	80.5	17.5	4.9	79.8	17.8
5.0	86.2	19.6	5.0	85.6	19.0	4.8	83.2	19.4
10.1	33.6	10.0	9.8	48.6	11.3	9.8	37.7	9.6
9.8	66.2	14.6	9.5	61.9	13.3	9.5	66.5	14.3
9.8	75.2	16.2	9.5	76.0	16.2	9.5	74.5	16.1
9.9	82.6	18.0	9.7	81.4	17.5	9.6	80.5	17.8
9.9	86.7	19.6	9.7	86.0	19.0	9.7	83.7	19.4
14.9	35.5	10.0	14.6	50.2	11.3	14.6	39.5	9.6
14.6	67.6	14.6	14.3	63.4	13.3	14.2	67.7	14.3
14.6	76.3	16.2	14.4	77.4	16.2	14.3	75.4	16.1
14.7	83.7	18.0	14.6	82.6	17.5	14.5	81.0	17.8
14.7	87.3	19.6	14.6	86.6	19.0	14.5	84.2	19.4
19.7	37.2	10.0	19.4	51.7	11.3	19.4	41.1	9.6
19.1	68.8	14.6	19.1	64.4	13.3	19.0	68.7	14.3
19.3	77.0	16.2	19.2	78.0	16.2	19.1	76.0	16.1
19.5	84.2	18.0	19.4	83.1	17.5	19.3	81.7	17.8
19.4	87.6	19.6	19.4	87.0	19.0	19.3	84.5	19.4
24.5	38.8	10.0	24.2	53.1	11.3	24.1	42.7	9.6
24.2	69.8	14.6	23.9	65.5	13.3	23.8	69.5	14.3
24.2	77.6	16.2	24.0	78.5	16.2	23.9	76.6	16.1
24.3	84.7	18.0	24.1	83.7	17.5	24.1	82.2	17.8
24.3	88.0	19.6	24.2	86.8	19.0	24.1	84.6	19.4

Table 3. Equilibrium temperature, equilibrium relative humidity, and equilibrium moisture content data for the adsorption experiments (2003 corn samples) for the yellow dent, white, and waxy corn types (average of three replicates).

Yellow Dent			White			Waxy		
Temp. (˚C)	ERH (%)	EMC (% w.b.)	Temp. (˚C)	ERH (%)	EMC (% w.b.)	Temp. (˚C)	ERH (%)	EMC (% w.b.)
0.4	45.5	11.3	0.2	46.2	10.8	0.2	49.7	10.8
0.3	61.1	13.7	0.1	58.5	12.7	0.0	63.8	13.4
0.5	71.7	15.5	0.3	72.4	15.5	0.3	68.8	14.6
0.5	82.2	18.0	0.4	80.4	17.1	0.4	79.1	17.2
0.5	87.6	20.0	0.5	85.8	19.3	0.2	84.2	19.5
5.2	47.7	11.3	5.0	48.2	10.8	4.9	51.5	10.8
5.0	63.1	13.7	4.8	60.2	12.7	4.7	64.3	13.4
5.1	73.4	15.5	4.9	74.3	15.5	4.9	70.4	14.6
5.1	83.1	18.0	5.0	81.5	17.1	5.0	79.7	17.2
5.2	88.0	20.0	5.0	86.2	19.3	5.0	84.6	19.5
10.0	49.9	11.3	9.8	49.9	10.8	9.8	53.2	10.8
9.8	65.1	13.7	9.6	61.9	12.7	9.5	65.4	13.4
9.8	75.0	15.5	9.7	75.3	15.5	9.7	72.2	14.6
9.9	84.4	18.0	9.8	82.5	17.1	9.8	81.3	17.2
10.0	88.6	20.0	9.8	86.7	19.3	9.8	85.0	19.5
14.8	51.8	11.3	14.6	51.5	10.8	14.5	54.6	10.8
14.6	66.6	13.7	14.4	63.3	12.7	14.3	66.5	13.4
14.6	76.1	15.5	14.5	76.3	15.5	14.4	73.0	14.6
14.7	85.3	18.0	14.6	83.2	17.1	14.6	81.7	17.2
14.8	89.1	20.0	14.6	87.0	19.3	14.6	85.3	19.5
19.6	57.3	11.3	19.4	52.4	10.8	19.3	55.8	10.8
19.4	67.8	13.7	19.2	64.1	12.7	19.0	67.4	13.4
19.4	76.9	15.5	19.2	77.0	15.5	19.2	73.8	14.6
19.5	85.7	18.0	19.4	83.9	17.1	19.4	82.2	17.2
19.5	89.3	20.0	19.4	87.3	19.3	19.3	85.5	19.5
24.4	55.1	11.3	24.2	53.9	10.8	24.1	57.0	10.8
24.2	68.8	13.7	24.0	65.2	12.7	23.8	68.2	13.4
24.2	77.5	15.5	24.0	77.4	15.5	24.0	74.3	14.6
24.4	86.2	18.0	24.2	84.2	17.1	24.2	82.6	17.2
24.4	89.5	20.0	24.2	86.9	19.3	24.2	85.3	19.5

EMC/ERH Experimental Results from the 2003 Corn Samples

Figure 1 compares the adsorption and desorption EMC/ERH relationships of the yellow dent corn type for two temperatures (0˚C and 25˚C). This chart clearly shows that, for the same temperature, the desorption curve was always above the adsorption curve. At MC values from 10% to 12%, the desorption curve was from 7 to 8 ERH percentage points lower than the adsorption curve. The effect of sorption tended to be smaller as MC increased. At MC values between 18% and 20%, the difference between the two curves was reduced to approximately one ERH percentage point. Temperature did not have a large effect on the difference between the adsorption and desorption curves. In terms of the effect on MC at constant ERH, the difference in MC ranged from 1.1 and 0.7 percentage points at 55% ERH for the 25˚C and 0˚C isotherms, respectively, to 0.4 percentage points at 85% ERH.

The effect of hybrid on the EMC/ERH desorption relationship of yellow dent, white, and waxy corn for 10˚C is shown in figure 2. The difference in EMC values for the three corn types varied from 0.3 to 1.2 percentage points over the range of ERH values investigated. At low MC values (below 15%), the curve of the yellow dent corn hybrid was above the curves of the white and waxy corn hybrids. Between 15% and 17% MC, the three corn types had a similar EMC/ERH relationship. Above 17% MC, the yellow dent and waxy corn types had a similar EMC/ERH relationship, while the curve for white corn was below the other two curves. It is important to point out that the difference among the EMC/ERH curves was as large as 8 ERH percentage points at low MC values, and 3 ERH percentage points at high MC values. In terms of the effect on MC at constant ERH, the difference in MC ranged from 0.9 percentage points at 50% ERH to 0.3 percentage points at 70% ERH and 1.2 percentage points at 85% ERH.

The Modified Chung-Pfost Model

Determination of the Parameter Set

Table 7 shows the A, B, and C parameters for the three corn types (yellow dent, white, and waxy corn) obtained by fitting the EMC/ERH sorption and desorption data to the modified Chung-Pfost model with the n-lin procedure in SAS. The results shown in table 7 indicate that the difference due to corn type (yellow dent, white, and waxy) was statistically significant (at the 95% confidence level) for at least one parameter (B). Therefore, this finding confirmed that the EMC/ERH relationship was different for different types of corn. The sorption effect was significant (at the 95% confidence level) for at least two parameters (A and B). This indicated that drying and rewetting processes have a different EMC relationship. Thus, desorption (drying) and adsorption (rewetting) parameters should be used instead of a single EMC relationship that ignores the difference.

The fit of the parameter sets of the modified Chung-Pfost equation obtained in this work was quantified using the residuals sum of squares, the mean relative deviation, and the

Table 4. Equilibrium temperature, equilibrium relative humidity, and equilibrium moisture content data for the desorption experiments (2004 corn samples) for the yellow dent and white corn types (average of three replicates).

Yellow Dent			White		
Temp. (˚C)	ERH (%)	EMC (% w.b.)	Temp. (˚C)	ERH (%)	EMC (% w.b.)
0.0	40.8	11.5	–0.2	40.7	11.1
–0.2	59.1	13.9	–0.5	63.0	14.2
0.0	71.9	16.1	–0.2	74.0	16.3
–0.1	82.2	18.5	–0.2	81.4	18.2
–0.2	85.7	19.5	–0.5	86.7	21.1
4.8	42.8	11.5	4.6	43.0	11.1
4.6	60.8	13.9	4.3	65.1	14.2
4.7	73.2	16.1	4.6	75.5	16.3
4.7	82.8	18.5	4.6	82.5	18.2
4.5	86.0	19.5	4.3	86.8	21.1
9.6	44.6	11.5	9.4	45.0	11.1
9.4	62.5	13.9	9.1	66.5	14.2
9.6	74.4	16.1	9.4	76.6	16.3
9.6	83.5	18.5	9.4	83.2	18.2
9.3	86.3	19.5	9.1	86.9	21.1
14.4	46.4	11.5	14.2	46.9	11.1
14.2	64.2	13.9	13.9	67.9	14.2
14.4	75.7	16.1	14.1	77.5	16.3
14.4	84.3	18.5	14.2	83.7	18.2
14.1	86.5	19.5	13.9	87.2	21.1
19.2	48.3	11.5	19.0	48.5	11.1
18.9	65.6	13.9	18.6	69.0	14.2
19.1	76.5	16.1	18.9	78.2	16.3
19.2	84.6	18.5	19.0	84.1	18.2
18.8	86.6	19.5	18.6	86.9	21.1
24.0	49.9	11.5	23.8	50.1	11.1
23.7	66.7	13.9	23.4	69.9	14.2
23.9	77.2	16.1	23.7	78.8	16.3
24.0	84.9	18.5	23.8	84.3	18.2
23.6	85.5	19.5	23.5	87.0	21.1
28.8	51.5	11.5	28.6	51.5	11.1
28.5	67.9	13.9	28.2	70.8	14.2
28.7	78.3	16.1	28.6	79.4	16.3
28.8	84.8	18.5	28.6	84.2	18.2
28.4	84.9	19.5	28.3	85.8	21.1

Table 5. Equilibrium temperature, equilibrium relative humidity, and equilibrium moisture content data for the adsorption experiments (2004 corn samples) for the yellow dent and white corn types (average of three replicates).

Yellow Dent			White		
Temp. (˚C)	ERH (%)	EMC (% w.b.)	Temp. (˚C)	ERH (%)	EMC (% w.b.)
–0.2	40.8	10.7	–0.3	43.3	11.0
–0.5	56.6	12.9	–0.5	56.5	12.8
–0.2	69.3	15.0	–0.2	70.3	15.3
–0.2	78.7	17.0	–0.2	79.3	17.3
–0.4	84.9	19.2	–0.4	84.5	19.3
4.6	43.7	10.7	4.6	45.4	11.0
4.3	59.1	12.9	4.3	58.4	12.8
4.6	70.9	15.0	4.6	71.8	15.3
4.6	79.5	17.0	4.6	79.9	17.3
4.4	85.3	19.2	4.3	84.8	19.3
9.4	45.5	10.7	9.4	47.4	11.0
9.1	60.8	12.9	9.1	59.9	12.8
9.4	72.2	15.0	9.4	73.3	15.3
9.4	80.3	17.0	9.4	80.9	17.3
9.2	85.7	19.2	9.1	85.2	19.3
14.1	47.3	10.7	14.2	49.3	11.0
13.7	62.3	12.9	13.9	61.8	12.8
14.2	73.3	15.0	14.2	74.5	15.3
14.3	81.1	17.0	14.2	81.7	17.3
14.0	85.8	19.2	13.9	85.5	19.3
19.0	49.1	10.7	19.0	51.0	11.0
18.6	63.7	12.9	18.7	63.2	12.8
19.0	74.4	15.0	19.0	75.5	15.3
19.0	81.7	17.0	19.0	82.4	17.3
18.8	85.9	19.2	18.7	85.7	19.3
23.7	50.0	10.7	23.8	53.4	11.0
23.4	64.7	12.9	23.5	64.2	12.8
23.8	75.1	15.0	23.8	76.1	15.3
23.9	82.2	17.0	23.9	82.8	17.3
23.6	85.6	19.2	23.5	85.5	19.3
28.6	51.5	10.7	28.6	53.7	11.0
28.2	65.5	12.9	28.3	65.2	12.8
28.6	75.8	15.0	28.6	76.9	15.3
28.7	82.4	17.0	28.7	83.0	17.3
28.3	85.0	19.2	28.4	85.3	19.3

standard error of the estimate (eqs. 3, 4, and 5, respectively). Table 8 shows the statistics for the desorption set of parameters. The fit for the white corn type was better than for the other two types (a lower value for each of the three statistics considered implies a better fit of the model). Second best was the fit for yellow dent corn, and last was the fit for waxy corn. A comparison of the desorption statistics to the adsorption statistics (tables 8 and 9) shows that, with the exception of the white corn, the modified Chung-Pfost model was able to predict the adsorption EMC/ERH relationship more accurately than the desorption EMC/ERH relationship. The best fit of the modified Chung-Pfost model with the adsorption set of parameters was for yellow dent corn, followed by the fit for white corn, and then the fit for waxy corn. The statistics for the three corn types investigated in this work were compared to the statistics reported for the set of desorption parameter values in ASAE Standard D245.5. This comparison showed that the parameters obtained in this research had a better fit to their original data than those of the current ASAE Standard (reported by Chen and Morey, 1989a). The MRD for the three corn types investigated in this work ranged from 1.9 to 2.6, compared to 4.3 for the ASAE Standard data. Similarly, the SE for the three corn types investigated in this work ranged from 1.6 to 1.9, versus 5.0 reported for the ASAE Standard data.

Table 6. Standard deviation ranges of the temperature, equilibrium moisture content (EMC), and equilibrium relative humidity (ERH) experimental data presented in tables 2 through 5.

	Corn Type	Sorption	Temp. (˚C)	EMC (%)	ERH (%)
2003					
	Yellow dent	Desorption	0.21-0.45	0.01-0.10	0.17-2.89
		Adsorption	0.15-0.42	0.00-0.13	0.11-2.69
	White	Desorption	0.17-0.46	0.04-0.16	0.10-2.66
		Adsorption	0.14-0.43	0.04-0.11	0.11-3.34
	Waxy	Desorption	0.15-0.58	0.03-0.52	0.06-2.40
		Adsorption	0.17-0.53	0.04-0.35	0.09-4.36
2004					
	Yellow dent	Desorption	0.00-0.12	0.06-0.12	0.01-1.02
		Adsorption	0.00-0.12	0.04-0.12	0.03-0.67
	White	Desorption	0.00-0.07	0.05-0.24	0.02-0.68
		Adsorption	0.00-0.03	0.03-0.10	0.03-1.39

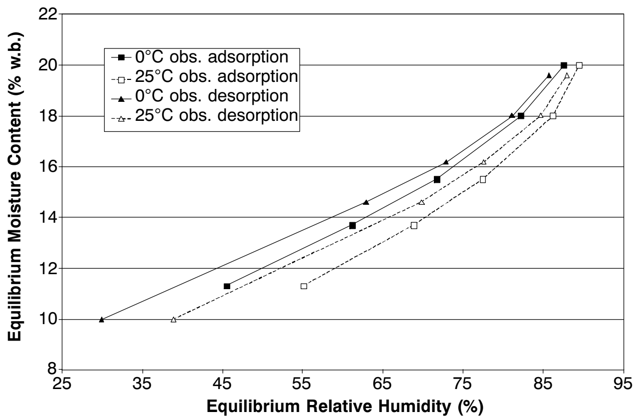

Figure 1. Observed EMC/ERH adsorption and desorption values (average of three replicates) for two different temperatures (0°C and 25°C) for the yellow dent corn hybrid.

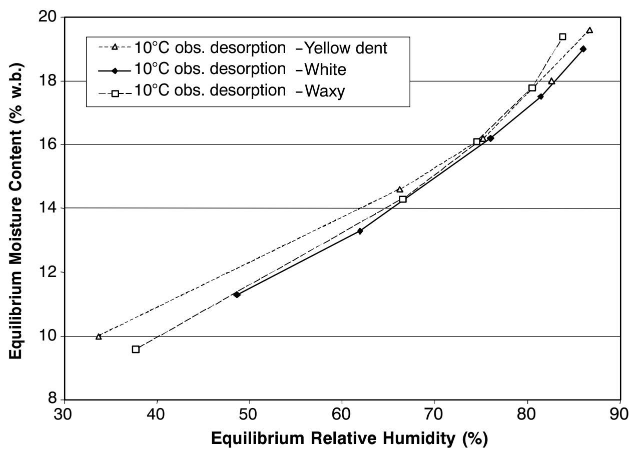

Figure 2. Observed EMC/ERH desorption values (average of three replicates) at 10°C for the yellow dent, white, and waxy corn hybrids.

Table 7. Adsorption and desorption *A*, *B*, and *C* parameters for the three corn types (yellow dent, white, and waxy).[a]

	A	*B*	*C*
Desorption			
Yellow dent	406.0441 a	16.6755 a	46.7212 a
White	288.6909 a	15.1571 b	47.2013 a
Waxy	253.3213 a	14.0873 c	46.3675 a
Adsorption			
Yellow dent	238.5935 b	15.0978 d	40.3216 a
White	239.7757 b	14.4332 e	49.5316 a
Waxy	173.6 b	12.3554 f	50.9301 a

[a] Values followed by different letters are significantly different at the 95% level.

Table 8. Residuals sum of squares (RSS), mean relative deviation (MRD), and standard error of the estimate (SE) for the modified Chung-Pfost equation and the set of desorption parameters for the yellow dent, white, and waxy corn types obtained in this research, and for the set of parameters from ASAE Standard D245.5 (data reported by Chen and Morey, 1989a).

Corn Type	RSS	MRD	SE
Yellow dent	84.9	2.4	1.7
White	69.2	1.9	1.5
Waxy	110.0	2.6	1.9
Chen and Morey	--	4.3	5.0

Table 9. Residuals sum of squares (RSS), mean relative deviation (MRD), and standard error of the estimate (SE) for the modified Chung-Pfost equation and the set of adsorption parameters for the yellow dent, white, and waxy corn types obtained in this research.

Corn Type	RSS	MRD	SE
Yellow dent	72.8	1.9	1.6
White	82.8	2.1	1.7
Waxy	97.2	2.2	1.8

Table 10. Residuals sum of squares (RSS), mean relative deviation (MRD), and standard error of the estimate (SE) for predicted EMC/ERH values using the modified Chung-Pfost equation and the set of parameters for the yellow dent and white corn types obtained in this research (2003 corn samples) and the 2004 EMC/ERH data.

Sorption	Corn Type	RSS	MRD	SE
Desorption	Yellow dent	554.4	2.7	2.3
	White	995.2	3.4	3.1
Adsorption	Yellow dent	731.3	3.3	2.6
	White	850.5	3.6	2.9

Validation of the Parameter Set Obtained from the 2003 Samples with the EMC/ERH Data from the 2004 Samples

The prediction of the modified Chung-Pfost model using the corn type-specific parameters developed from the 2003 corn samples was validated using the EMC/ERH data obtained from the 2004 corn samples. The validation was done for the yellow dent and white corn samples. Table 10 shows the SE, RSS, and MRD computed from the validation set.

The validation shows that the model predicted the EMC/ERH relationship of the 2003 corn samples better than the relationship of the 2004 corn samples. This was expected because the parameters for the model were obtained using the 2003 corn samples and it is possible that the EMC relationship is affected by growing conditions. The RSS increased considerably when compared to the values of tables 8 and 9 (553% to 1482%). The RSS (eq. 3) is highly affected by the number of data points in the experiment. For the 2004 corn sample EMC/ERH experiment, an additional temperature (30°C) was considered. This implied 15 extra data points in the validation of the model compared to the 2003 experiment. The MRD and SE for the yellow dent corn and desorption increased by 12.5% and 35%, respectively, while for white corn, the increase of these two statistics was 79% and 107%, respectively. The prediction of the adsorption relationship was affected similarly. The MRD and SE increased by 74% and 62%, respectively, for yellow dent corn and by 71% for white corn (for both MRD and SE). Overall, the prediction for yellow dent corn was better than for white corn. This was most likely due to the fact that the same hybrid was considered for the yellow dent corn experiment in both years, while a composite sample of white corn was used, and it included different hybrids in 2003 versus 2004. The remarkable result of this validation is, however, that when the modified Chung-Pfost model using the 2003 corn sample parameters was validated against a new set of EMC/ERH data obtained from samples from the 2004 harvest season, it had a lower SE and MRD than the fit of the model in the current ASAE Standard to its original data. The MRD and SE of the Chen and Morey (1989a) parameters for yellow dent corn and desorption were 4.3 and 5.0, respectively, while in this validation, the MRD and SE for corn types from two different harvests were 2.7 and 2.3, respectively.

Table 11. Values for parameters *A*, *B*, and *C* of the modified Chung-Pfost equation from ASAE Standards D245.4 and D245.5.

Parameter	ASAE Standard D245.4	ASAE Standard D245.5
A	312.3	374.34
B	16.958	18.662
C	30.205	31.696

This validation indicates that, even though the year-to-year variability of a given corn type affects the EMC/ERH relationship, the variation was not large enough to require yearly evaluation of the EMC/ERH relationship for the same corn hybrid.

Comparison of the Modified Chung-Pfost EMC Relationship Using the Set of Parameters Obtained in this Experiment Versus the Set of Parameters from the ASAE Standard

ASAE Standard D245.4 gave a different set of values for the *A*, *B*, and *C* parameters for yellow dent corn than the newer version of the standard (ASAE Standard D245.5; *ASAE Standards*, 2001). The old equation parameter values (D245.4) were based on the work of Pfost et al. (1976). Later (Sokhansanj and Yang, 1996), the parameter values for the modified Chung-Pfost equation were changed on the basis of the findings of Chen and Morey (1989a). Table 11 shows the two sets of parameter values from the ASAE Standards.

It was previously shown (fig. 2) that different corn types and hybrids have different EMC/ERH curves. The modified Chung-Pfost parameter values published in the current ASAE Standard were obtained for a specific yellow dent corn hybrid (Dekalb 484). The previous ASAE Standard (D245.4) provided a different set of parameter values for the modified Chung-Pfost equation for an unknown corn hybrid. These parameters from the two ASAE Standards (D245.4 and D245.5) were different, most likely due to the different corn hybrids used for their determination.

Figure 3 shows the desorption EMC/ERH relationship for 15°C constructed using the modified Chung-Pfost equation with the set of parameters from ASAE Standards D245.4 and D245.5 (table 11) and the desorption parameters for the yellow dent, white, and waxy corn types obtained in this study (table 7). From this figure, it can be seen that the curve for yellow dent corn from this research is almost identical to the curve generated using the parameters from ASAE Standard D245.4 for corn, and substantially different from the curve corresponding to the ASAE Standard D245.5. As previously explained, the white and waxy corn curves are different from the yellow dent corn curve.

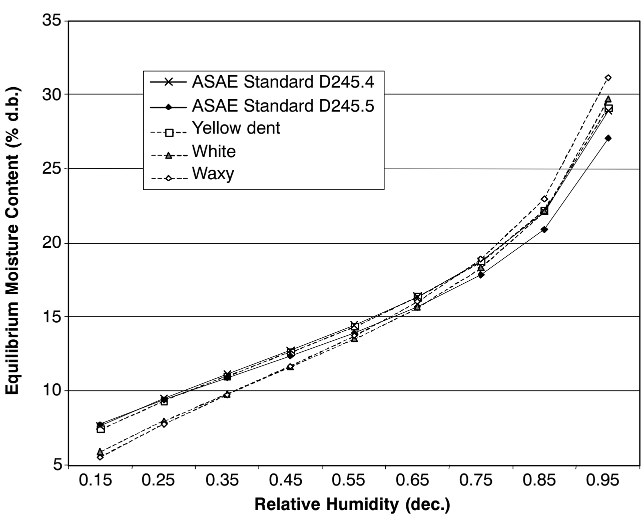

Figure 3. Comparison of predicted corn EMC/ERH desorption relationship for the 2003 experimental data (yellow dent, white, and waxy corn) at 15°C with yellow dent corn EMC/ERH relationship from ASAE Standards D245.4 and D245.5.

Table 12. Average of the difference between EMC (%) determined with the modified Chung-Pfost equation and the ASAE Standard D245.4 set of parameters and the set of parameters determined in this research (temp. range = 0°C to 30°C; RH range = 15% to 95%).

	Temperature (°C)						
Corn Type	0	5	10	15	20	25	30
Yellow dent	0.73	0.44	0.21	0.09	0.13	0.25	0.36
White	1.37	1.18	1.04	0.94	0.88	0.83	0.79
Waxy	1.35	1.26	1.20	1.17	1.15	1.14	1.13

Table 13. Average of the difference between EMC (%) determined with the modified Chung-Pfost equation and the ASAE Standard D245.5 set of parameters and the set of parameters determined in this research (temp. range = 0°C to 30°C; RH range= 15% to 95%).

	Temperature (°C)						
Corn Type	0	5	10	15	20	25	30
Yellow dent	0.55	0.58	0.63	0.68	0.73	0.78	0.82
White	1.18	1.14	1.11	1.10	1.09	1.09	1.09
Waxy	1.51	1.51	1.50	1.50	1.50	1.51	1.51

The difference between the predicted EMC values using the set of parameters obtained in this research with those of the ASAE Standard was quantified. It was observed that the differences were generally smaller when compared to ASAE Standard D245.4 (table 12) than when compared to ASAE Standard D245.5 (table 13) for the three corn types. As was expected, the predicted EMC data using the ASAE Standard parameters was closer to the yellow dent corn hybrid than to the white or waxy corn types investigated in this research. When the yellow dent corn hybrid was compared to the D245.4 data, the difference ranged from 0.09% at 15°C to 0.73% at 0°C; when compared to the D245.5 data, the difference ranged from 0.55% at 0°C to 0.82% at 30°C. However, the difference for white corn ranged from 0.79% at 30°C to 1.37% at 0°C when compared to the D245.4 set of parameters, and from 1.09% at 20°C or higher to 1.18% at 0°C when compared to the D245.5 set of parameters. Similarly, the difference for waxy corn ranged from 1.13% at 30°C to 1.35% at 0°C for the D245.4 set of parameters and from 1.50% to 1.51% for the D245.5 set of parameters.

These results clearly show that the differences among the ASAE Standard prediction and the prediction for the EMC of the white and waxy corn types were substantial. Thus, the use of corn type-specific sets of parameters to predict the EMC/ERH relationship is recommended instead of the universal use of the current ASAE Standard parameters for yellow dent corn. Additionally, the desorption EMC/ERH relationship obtained with ASAE Standard D245.4 was closer to the relationship for the yellow dent corn hybrid obtained in this study than the EMC/ERH relationship obtained with the current ASAE Standard D245.5. This suggest that further research and discussion is required to ensure that the desorption EMC relationship for yellow dent corn provided in the ASAE Standard is representative of the yellow dent corn hybrids available in the market.

Conclusions

The EMC relationships for adsorption and desorption of three different corn types (yellow dent, white, and waxy) were investigated using corn samples obtained during the 2003 harvest. In this research, one parameter (*B*) for the modified Chung-Pfost equation was found to be significantly different for each corn type. In addition, two adsorption parameters (*A* and *B*) were statistically different from the respective desorption parameters.

The parameters of the modified Chung-Pfost equation found in this research were compared to those of the ASAE Standard. It was determined that the desorption EMC/ERH relationship obtained from the ASAE Standard was significantly different from the relationship for the yellow dent, white, and waxy corn types.

The EMC/ERH data obtained from the 2004 corn samples was used for the validation of the adsorption and desorption parameters for the modified Chung-Pfost equation obtained the year before for the yellow dent and white corn types. It showed that the model was able to predict the EMC/ERH relationship with a low error: from 2.3 to 3.1 for the standard error (SE) and from 2.7 to 3.6 for mean relative deviation (MRD).

Based on the results of this research, the use of adsorption/desorption and corn type-specific EMC/ERH relationships is recommended in order to improve the EMC prediction of the modified Chung-Pfost equation.

This research also suggests that a revision of ASAE Standard D245.5 should include: (1) the set of adsorption and desorption parameters for white and waxy corn types developed in this study, (2) the set of adsorption parameters for the yellow dent corn type developed in this study, (3) consideration of the set of desorption parameters for the yellow dent corn type developed in this study, and (4) recommendations for the experimental procedure for conducting adsorption and desorption EMC experiments (i.e., procedures for conditioning the grain samples at different moisture contents for both the desorption and adsorption experiments, the temperature range at which the conditioning of the grain samples should be performed, the time required for allowing the grain sample to equilibrate after rewetting, etc). Further research and discussion are required in order to adopt a standard set of desorption parameter values for the yellow dent corn type that represents the majority of the yellow dent corn hybrids available in the market.

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