TECHNICAL NOTE:

EQUILIBRIUM MOISTURE CONTENTS OF ROUGH RICE DRIED USING HIGH-TEMPERATURE, FLUIDIZED-BED CONDITIONS

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ABSTRACT. *Desorption isotherms of long-grain rough rice with initial moisture content of 20.6% (wet basis) and dried in a fluidized-bed system at temperatures ranging from 60°C to 90°C and relative humidities from 7% to 75% were measured. Rice sample mass and drying air conditions were recorded throughout the drying duration for each test until a steady-state mass was attained. The Page equation, with experimentally determined drying parameters, was used to describe the drying data. Equilibrium moisture contents were used to estimate empirical constants of the modified Chung-Pfost equation. The resulting modified Chung-Pfost equation described the experimental data with a root mean square error (RMSE) of 0.73 and a coefficient of determination (R^2) of 0.94.*

Keywords. *Desorption, Equilibrium moisture content, Isotherms, Modified Chung-Pfost equation, Rough rice.*

The main consideration in commercial drying of rough rice is reducing moisture content (MC; moisture content is expressed on a wet basis unless specified otherwise) in the shortest duration possible without adversely affecting milling quality. For the years 2008 and 2009, approximately 9.26 million tons of rice was harvested in the U.S. (USDA, 2010). These high production rates were supported by greater combine and transport capacities, which in turn placed increased pressure on driers. Increased drying speed, afforded by shorter drying durations, would enable drying facilities to increase throughput and thus meet the need to dry increasing crop influx.

A recent approach to rapid drying of high-MC rough rice utilizes high-temperature, fluidized-bed drying conditions (Soponronnarit et al., 1996). This technology offers several features: (1) an even flow of fluidized kernels permits continuous, large-scale operations with ease of product handling; (2) high heat and mass transfer rates create rapid movement of moisture from individually exposed kernels to air; and (3) rapid mixing of fluidized kernels leads to uniform drying throughout the fluidized bed, enabling better control of the drying process (Hovmand, 1987).

Fluidized-bed drying is being used commercially for drying rice in Asia. In fluidized-bed drying, air temperature and bed thickness have been shown to be the main factors affecting rough rice drying rate (Tumambing and Driscol, 1991) while milling quality and color were dependent on the MC at which the rough rice exited the drier (Sutherland and Ghaly, 1990; Wetchacama et al., 2000). Drying air temperatures ranging from 140°C to 150°C, air velocity ranging from 2.0 to 3.0 m s^{-1}, and bed thickness of up to 10 cm have been recommended for fluidized-bed drying of high-MC rough rice (higher than 23%) to maximize efficiency while maintaining quality (Soponronnarit and Prachayawarakorn, 1994). However, fluidized-bed drying has not been accepted in the U.S. In order to facilitate this possible acceptance, research is needed to fully quantify the kinetics of fluidized-bed rice drying under varying temperature and relative humidity (RH) conditions using U.S. rice cultivars. A key property necessary for this quantification is equilibrium moisture content (EMC) corresponding to a given temperature and equilibrium relative humidity (ERH) (Sun and Woods, 1997a, 1997b).

Equilibrium moisture content, defined as the MC at which hygroscopic particles are neither gaining nor losing moisture, is dynamic and depends on the temperature and RH of the surrounding air. The two basic techniques used to measure EMC of foods and agricultural materials are the manometric and gravimetric methods (Gal, 1975, 1981). Manometric methods are based on vapor pressure measurements in the sample environments, while gravimetric methods measure changes in mass.

Many studies have employed the use of mathematical models to describe EMC/ERH/temperature relationships in complex drying systems (Iguaz and Versada, 2007; Aviara et al., 2004; Basunia and Abe, 2001; Chen and Morey, 1989; Sun and Byrne, 1998; Sun and Woods, 1994). ASABE Standard D245.6 (*ASABE Standards*, 2007) lists the modified Chung-Pfost (Chung and Pfost, 1967), modified Halsey (Chirife and Iglesias, 1978), modified Henderson (Henderson, 1952), modified Oswin (Chen, 1988; Oswin, 1946), and the Guggenheim-Anderson-deBoer (GAB) as equations that can be used for modeling grain sorption equilibria data.

Studies have reported the modified Chung-Pfost and modified GAB equations as the most satisfactory theoretical isotherm/EMC models (Iguaz and Versada, 2007; Multon, 1998; Van der Berg, 1984; Weisner, 1985; Speiss and Wolf, 1987). Iguaz and Versada (2007) reported the modified Chung-Pfost and modified GAB models to be most appropriate in estimat-

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ing EMC of rough rice at temperatures ranging from 40°C to 80°C. Basunia and Abe (2001) reported the modified Chung-Pfost as the best in the range of 12°C to 51°C, while Sun (1999) identified the modified Chung-Pfost as most appropriate for describing EMC/ERH sorption isotherms for wheat. The modified Chung-Pfost equation is given as follows:

$$M_e = \frac{-1}{B} Ln\left[\frac{-(T+C)LnRH}{A}\right] \qquad (1)$$

where RH is relative humidity (decimal), T is temperature (°C), M_e is equilibrium moisture content (% dry basis), and A, B, and C are grain-specific empirical constants.

Moisture content dry basis is given by:

$$MC_{dry\text{-}basis} = \frac{100 \times MC_{\text{wet-}basis}}{100 - MC_{\text{wet-}basis}} \qquad (2)$$

Considering that fluidized-bed drying utilizes drying air temperatures that are not commonly used in the U.S. drying industry, there is need to evaluate the modified Chung-Pfost equation for estimating EMC at these high-temperature conditions. Therefore, the objectives of this study were to: (1) measure the desorption isotherms of long-grain rough rice subjected to elevated drying air temperatures in a laboratory-scale, fluidized-bed system; and (2) evaluate the appropriateness of the modified Chung-Pfost equation for estimating equilibrium data of rough rice for the range of temperatures and RH studied.

Materials and Methods

Test System

A 0.91 m^3 (32 ft^3) environmental chamber (Platinous Sterling Series T and RH chamber, ESPEC North America, Hudsonville, Mich.) was utilized to produce drying air at set temperature and RH conditions (fig. 1). The chamber was capable of maintaining air conditions at set levels within a range of temperatures (-35°C to 150°C) and RH values (6% to 98%). The air in the oven was circulated at 0.38 m^3 s^{-1}, and conditions were monitored using a digital temperature and RH probe (Hygro-M2, General Eastern, Woburn, Mass.). The digital RH probe was calibrated using potassium sulfate, sodium chloride, and lithium chloride (Merck, Darmstadt, Germany) prior to the start of the experiment.

A metal cylinder, 20.3 cm (8 in.) in diameter and 61.0 cm (24 in.) tall, with a perforated floor to hold rice samples for drying, was mounted to a metal plenum. This drying apparatus was placed inside the environmental chamber. The drying cylinder was wrapped with 2 mm (0.02 in.) thick, ceramic fiber insulation (Zirconia Felt ZY-50, Zircar Zirconia, Inc., Florida, N.Y.). A 25.4 cm (10 in.) diameter centrifugal fan (4C108, Dayton Electric Manufacturing Co., Niles, Ill.), coupled to a 0.56 kW (0.75 hp), three-phase electric motor (3N443BA, Dayton Electric Manufacturer Co.), was mounted outside the chamber to avoid high temperature exposure. This fan suctioned air at set temperature and RH from the chamber through a port located in the chamber wall, and then passed the exhaust air through a second port in the chamber wall connected to the plenum beneath the drying cylinder. The desired airflow rate through the drying cylinder was achieved by regulating the electrical frequency of the fan motor using a frequency inverter (AF-300 Mini, GE Fuji Drives USA, Salem, Va.), which controlled the motor and fan shaft rotational speed.

A spring-loaded damper constructed in the plenum controlled airflow direction by either diverting air through the perforated floor or closing off the perforated floor, allowing the air to empty into the environmental chamber. Opening and closing of the spring-loaded damper was controlled by a linear actuator (damper actuator) (LACT4P, SPAL USA, Ankeney, Iowa) mounted outside the environmental chamber and connected to the damper by a cable that passed through a port in the chamber ceiling. A second linear actuator (load cell actuator) (LACT4P, SPAL USA, Ankeney, Iowa) mounted outside the environmental chamber and directly above the drying cylinder was coupled to a 178 N (40 lb_f) full-bridge, thin-beam load cell (LCL-040, Omega Engineering, Inc., Stanford, Conn.) that was attached to the drying cylinder via a cable that passed through a second port in the chamber ceiling.

At specified durations, the damper actuator was activated to raise the spring-loaded damper, thereby preventing airflow through the rice sample. The load cell actuator was then activated to suspend the drying cylinder just above the drying apparatus plenum. After a stabilization period, the mass of the drying cylinder and sample was recorded as a millivolt signal from the load cell. Voltage data were converted to masses using a previously established calibration. The weighing procedure, which lasted 30 s, was repeated at selected intervals during a drying trial until the mass remained approximately constant, varying by less than 0.01 g. Temperature and load cell data were collected using a data logger (21X micrologger, Campbell Scientific, Salt Lake City, Utah) and stored on a computer (Latitude C810, Dell Computer Corp., Round Rock, Tex.).

Measurement of Airflow Rates

Prior to drying trials, fan performance tests were conducted using a metal duct, 15.2 cm (6 in.) in diameter and 1.8 m (6 ft) in length, to establish the relationship of the fan motor electrical frequency and airflow rate for the circulation fan. Airflow rates were adjusted by varying the fan motor electrical frequency from 40 to 60 Hz. Average air velocity in the test duct was measured using a hot-wire anemometer (8450-13E-V-STD-NC, Control Co., Friendswood, Tex.).

Also prior to drying trials, the airflow rate/electrical frequency needed for fluidization of a 5.1 cm (2 in.) rough rice bed in the drying cylinder was determined. The procedure of Subramani et al. (2007) was used to determine minimum fluidization velocity at 60°C, 70°C, 80°C, and 90°C. A known mass of rice required to attain a 5.1 cm (2 in.) grain depth was poured into the drying cylinder. The fan was turned on, and air velocity increased to fluidize the bed of rice vigorously. The air velocity was then slowly decreased until the fluidized bed was reduced to a fixed bed. The pressure drop at different depths across the 5.1 cm (2 in.) rice bed was determined by inserting a static pressure probe from the top of the cylinder. At minimum fluidization velocity, the pressure drop across the bed was constant and the weight of rice was supported by the airflow (Subramani et al., 2007).

Rice Samples

Long-grain rice (Cybonnett) was harvested at the University of Arkansas Northeast Research and Extension Center

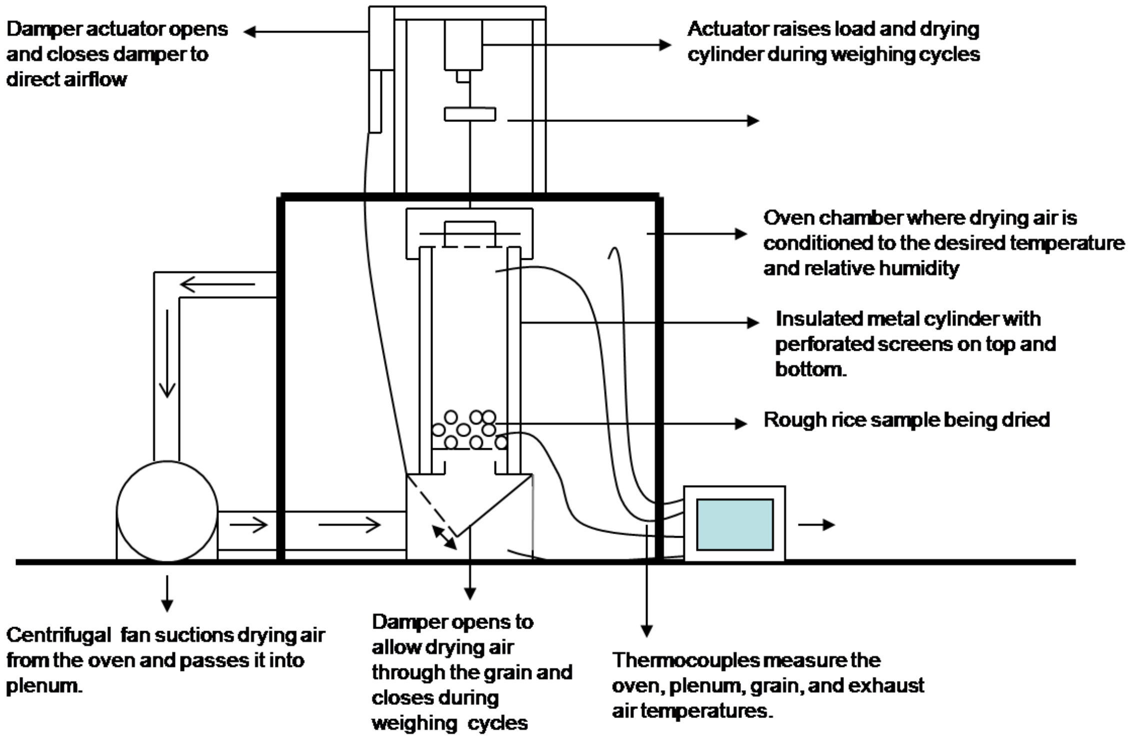

Figure 1. Schematic of the high-temperature, fluidized-bed drying system.

near Keiser, Arkansas, on 28 August 2007 at approximately 20.6% MC. The rice was cleaned using a dockage tester (XT4, Carter Day Co., Minneapolis, Minn.) and placed in storage at 4°C for two months. Prior to each drying trial, samples were withdrawn from storage, sealed in plastic bags, and allowed to equilibrate to room temperature (20°C) overnight. The MCs of the rice samples were then measured by drying duplicate, 15 g (0.033 lb_m) samples for 24 h in a convection oven (1370 FM, Sheldon, Inc., Cornelius, Ore.) maintained at 130°C (Jindal and Siebenmorgen, 1987).

Drying Procedure

A 1.11 kg (2.45 lb_m) rice sample, which was required to attain a 5.1 cm (2 in.) grain depth, was placed in the drying cylinder. A screen was placed on top of the cylinder to prevent inadvertent removal of fluidized kernels. The drying apparatus was then placed inside the environmental chamber and attached to the load cell actuator. The chamber control system was then activated to establish the desired temperature and RH air conditions within the chamber. During this stabilization period (lasting about 10 min), the damper actuator was activated to set the spring-loaded damper in the closed position, thus blocking air from passing through the rice sample. Once the chamber temperature and RH were stabilized, the combined mass of the drying cylinder and initial mass of the rice sample was measured by activating the load cell actuator. At the end of the weighing cycle, the load cell actuator was deactivated, followed by the deactivation of the damper actuator, which allowed airflow through the drying cylinder to initiate drying (fig. 1).

After a given drying duration, the damper was closed and the weighing procedure was repeated. This procedure was repeated every 5 min for the duration of a drying trial until the change in mass was less than 0.01 g. The drying data were converted to MCs by using the sample mass and MC at the beginning of the drying trial. To facilitate non-linear regression analysis of the drying data, arbitrary *k* and *n* values of 0.1 and 0.7, respectively (estimated using data from preliminary tests), and theoretical EMCs estimated using the modified Chung-Pfost equation, with *A*, *B*, and *C* values from ASABE Standard D245.6 (*ASABE Standards*, 2007) were specified for the Page equation (Page, 1949):

$$MR = \frac{M - M_e}{M_i - M_e} = e^{-kt^n} \quad (3)$$

where MR is the moisture ratio, M_i is the initial moisture content (dry basis), M is the moisture content (dry basis) after a given drying duration t (h), M_e is the equilibrium moisture content (dry basis), and k and n are drying constants.

Non-linear regression of the Page equation and the experimental data was then performed through a series of iterative steps to determine the actual *k* and *n* values for each air condition. The asymptotic values of the Page equation were used as the estimation of EMCs for given air temperature and RH conditions.

Results and Discussion

A total of 72 trials were conducted, comprising four air temperatures, six relative humidities at each temperature, and three replications for each drying condition. Sample plots of MC vs. drying duration are shown in figures 2 and 3. The drying constants *k* and *n* and the corresponding root mean square error (RMSE) determined from the nonlinear regression analysis (JMP. 8.0.1, SAS Institute, Inc., Cary, N.C.) of the Page equation are shown in table 1. The low RMSE values (<0.08) indicated that the Page equation adequately described the experimental data, providing good drying curve estimates.

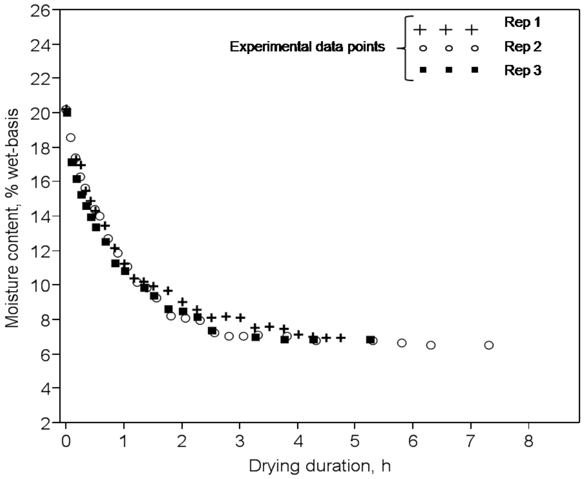

Figure 2. Fluidized-bed drying data for Cybonnett rice samples dried at 60°C and 7% RH.

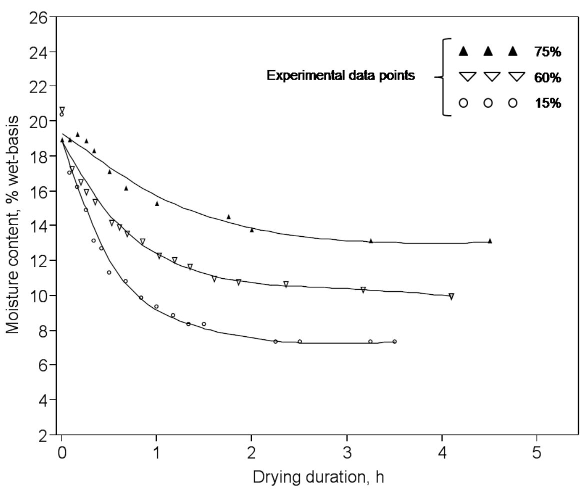

Figure 3. Fluidized-bed drying data for Cybonnett rice samples dried at 60°C and 15%, 60%, and 75% RH. The solid lines illustrate trends in the drying data.

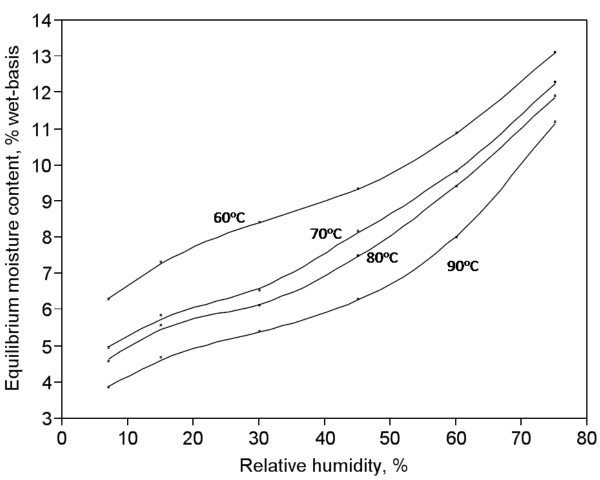

Figure 4. Equilibrium moisture contents (%, wet basis), determined as asymptotic values of the Page equation (eq. 3) for Cybonnett rice samples dried at 60°C to 90°C and 7% to 75% RH in a fluidized-bed system. Each data point is an average of three replications.

Table 1. Parameters *k* and *n*, and root mean square error (RMSE), a statistical estimate of goodness of fit, determined by nonlinear regression analysis of the Page equation (eq. 3) with experimental data for Cybonnett rice samples dried in a fluidized-bed system at 60°C to 90°C and 7% to 75% RH. Each value is an average of three replications.

		Relative Humidity					
Temperature		7%	15%	30%	45%	60%	75%
60°C	*k*	1.2353	1.7918	1.6589	1.5808	1.4034	0.4429
	n	0.8064	0.7087	0.8287	0.7133	0.7853	0.8841
	RMSE	0.02	0.03	0.04	0.04	0.06	0.09
70°C	*k*	1.4633	1.6334	1.6536	1.7174	1.6449	1.3668
	n	0.7195	0.6115	0.7545	0.8933	1.0129	0.7905
	RMSE	0.04	0.03	0.03	0.03	0.04	0.06
80°C	*k*	1.9933	2.1268	3.3679	2.5098	1.8470	2.3987
	n	0.6269	0.7497	0.9237	0.8853	1.0492	1.2231
	RMSE	0.02	0.04	0.04	0.04	0.04	0.05
90°C	*k*	2.1530	3.5369	3.3055	5.1912	2.4537	2.6029
	n	0.5656	0.7644	0.7220	1.1063	1.0368	1.4975
	RMSE	0.02	0.03	0.03	0.03	0.03	0.04

Table 2. Equilibrium moisture contents (%, wet basis), determined as asymptotic values of the Page equation (eq. 3) for Cybonnett rice samples dried in a fluidized-bed system at 60°C to 90°C and 7% to 75% RH. Each value is an average of three replications.

		Relative Humidity					
Temperature		7%	15%	30%	45%	60%	75%
60°C	Mean	6.5	7.3	8.4	9.3	10.9	13.1
	SD	0.06	0.08	0.09	0.26	0.25	0.12
70°C	Mean	5.3	5.8	6.5	8.2	9.5	12.3
	SD	0.06	0.03	0.16	0.10	0.04	0.08
80°C	Mean	4.6	5.6	6.1	7.5	9.4	11.9
	SD	0.10	0.07	0.20	0.03	0.14	0.11
90°C	Mean	3.8	4.7	5.4	6.3	8.0	11.2
	SD	0.17	0.03	0.13	0.15	0.15	0.14

Table 2 shows the EMCs determined as asymptotic values of the Page equation for each temperature and RH combination. There were no significant differences (p-values > 0.05) between replications for all drying conditions. As expected, greater EMCs were measured at greater RH values for the same drying air temperature, and lesser EMCs were measured at greater temperatures for the same RH. Similar trends have been reported by Iguaz and Versada (2007), Chowdhury et al. (2005), Aviara et al. (2004), and Imprasit and Noomhorm (2001). The EMC vs. RH patterns shown in figure 4 illustrates a clear effect of temperature and are similar to the Type II isotherms proposed by Brunauer et al. (1940).

Multiple linear regressions, a statistical analysis used to determine the effect of one or more independent variables on the dependent variable, was used to determine the effects of temperature and RH and their interactions on EMC. Results showed that the linear effects of both temperature and RH were highly significant (p-values < 0.0001), but there was no significant interaction effect of the two factors on EMC (p-value 0.5602).

The three parameters (A, B, and C) of the modified Chung-Pfost equation were estimated using non-linear regression analysis by means of the software JMP. 8.0.1(SAS Institute, Inc., Cary, N.C.). The ability of the modified Chung-Pfost equation to accurately estimate EMC was evaluated quantitatively using the RMSE and coefficient of determination (R^2). In addition, the pattern of residual plots (i.e., differences be–

Table 3. Estimates of coefficients *A*, *B*, and *C* of the modified Chung-Pfost equation from ASABE Standard D245.6 (*ASABE Standards*, 2007), Iguaz and Versada (2007), and non-linear regression analysis of the experimental data, and statistical evaluation parameters.

Source	*A*	*B*	*C*	R^2	RMSE	Pattern of Residuals
ASABE Standard	412.02	0.17528	39.016	0.89	1.04	Random
Iguaz and Versada (2007)	277.09	0.179	16.912	0.90	0.98	Random
This experiment	438.03	0.3219	−36.994	0.94	0.73	Random

tween measured and estimated values) was considered as a qualitative criterion in evaluating the appropriateness of this model (Chen and Wu, 2001).

Estimates of parameters *A*, *B*, and *C* of the modified Chung-Pfost equation and the statistical indices used to validate the appropriateness of the model (i.e., RMSE, R^2, and patterns of residuals) are shown in table 3. Estimated EMCs from the modified Chung-Pfost equation with parameters *A*, *B*, and *C* obtained from ASABE Standard D245.6 (*ASABE Standards*, 2007) and from a previous study conducted using the same air conditions (Iguaz and Versada, 2007) were compared to the experimental data. Results showed that the modified Chung-Pfost equation with statistically estimated parameters (*A*, *B*, and *C*) gave the best fit, with R^2 of 0.94 and RMSE of 0.73.

Conclusion

The equilibrium moisture contents of long-grain rough rice (Cybonnett) were measured using a fluidized-bed drying system. Using *A*, *B*, and *C* values statistically estimated from the test data, the modified Chung-Pfost equation was found acceptable for estimating EMCs at temperatures ranging from 60°C to 90°C and RH values from 7% to 75%.

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