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Best fitted thin-layer re-wetting model for medium-grain rough rice

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Five commonly cited thin-layer rewetting models, that is, Diffusion, Page, Exponential, Approximate form of diffusion and Polynomial were compared for their ability to fit the experimental re-wetting data of medium grain of rough rice, based on the standard error of estimate (SEE) of the measured and simulated moisture contents. The comparison shows that the Diffusion and the Page models have almost the same ability to fit the re-wetting experimental data of rough rice. The Exponential, the Approximate form of diffusion and the Polynomial models have less fitting ability than the Diffusion and the Page models for the entire period (> 4 days) of re-wetting of 25 tests at different combinations of temperatures (17.8 to 45°C) and relative humidites (56.0 to 89.3%). The Diffusion and the Page models were found to be most suitable equations, the average SEE value was less than 0.0015 (dry-basis, decimal), respectively, to describe the thin-layer re-wetting characteristics of rough rice over a typical five day re-wetting. These two models can be used for the simulation of deep-bed re-wetting of rough rice occurring during ventilated storage.

Key words: Thin-layer, rough rice, re-wetting parameters, temperature, relative humidity.

INTRODUCTION

International rice prices have been increasing in recent years. According to the crop prospects and food situation report, at the end of March in 2008, the rice prices were nearly double those of the previous year (FAO, 2008). Increased rice price forced several countries to rebuild their rice stocks. Thus, the increased price makes rice storage and improvement of rice storage techniques increasingly important because the deterioration in rice quality during storage results in considerable economic losses (Genkawa et al., 2008a). Moisture content is one of the most important factors influencing the quality of rough rice during storage and it remains at a high level, 18 to 30% wet-basis, during the harvest and must be reduced to, 14 to 15% wet-basis, with an appropriate drying process (Hacihafizoğlu et al., 2008). In addition, low-moisture rice is likely to crack due to rapid water adsorption (Siebenmorgen and Jindal, 1986; Banaszek and Siebenmorgen, 1990), and the cracking of rice results in breakage of kernels during milling and decrease head rice yield (Cnossen et al., 2003; Iguaz et al., 2006). Hence, it is necessary for low moisture rice to be conditioned by increasing its moisture content to prevent a decline in its eating quality (Genkawa et al., 2008b).

To design a rough rice drying equipment adequately, data are required both for drying and re-wetting characteristics from low to high temperatures. Moisture adsorption occurs when the vapour pressure within kernels is lower than the vapour pressure of the surrounding air. The moisture adsorbing environments can exist in the field before harvesting and subsequently during harvesting, holding, transport, drying and storage (Kunze and Prasad, 1978). Kunze (1988) stated that when rice in the field reaches moisture content of 30%

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or below, there already may be grains which are sufficiently dry to fissure when they readsorb moisture. The lower the moisture content of the rice in the field, the higher in general is the percentage of fissured grains. Kernels can fissure in the field by first drying during the day and then rapidly readsorbing moisture during the evening or night. The grain is exposed to fluctuating air temperatures and relative humidities causing drying and re-wetting cycles in low temperature drying. Grain prepared by desorption has a higher moisture content at a given relative humidity than grain prepared by adsorption. In both the near-ambient and natural drying process, ambient air is forced through the stored grain. For both processes, it is common to run the fan continuously even if it involves running the fan during periods of high ambient relative humidity which can cause re-wetting of grain. It is desirable to know how fast a grain bed would re-wet when the fans are running during high humidity periods.

Both moisture adsorption and desorption are equally important concerns when developing models simulating deep bed drying and aeration of grain. In the early stage of deep bed drying, the lower layer of grain desorbs moisture while the upper layer of grain adsorbs moisture. Thin-layer moisture transfer equations are used in simulation models for deep bed drying of grains. Most of the earlier studies on thin-layer moisture transfer relationships were concerned with thin-layer drying of cereal grains or oilseeds for a short duration and very little work was done on thin-layer re-wetting rates (Misra and Brooker, 1980; Jayas and Sokhansanj, 1986, 1988; Basunia and Abe, 1999, 2005). Sokhansanj et al. (1984) stated that the drying rate of wheat, barley and canola changes as a result of re-wetting. Limited work has been done in developing thin-layer re-wetting equations for rough rice. Much research has been conducted to develop thin-layer drying equations and to better understand the desorption phenomenon in rice (Agrawal and Singh, 1977, 1984; Wang and Singh, 1978; Noomhorn and Verma, 1986; Basunia and Abe, 1998, 2001). Far less research has been devoted to developing thin-layer adsorption equations. Genkawa et al. (2008a) developed a re-wetting method for brown rice by using film packaging technique and established a mathematical model suitable for designing the packaging. The moisture content of brown rice was increased from 10% wet-basis (w.b.) to 19% w.b. without cracking when the polymeric package was exposed to a humid environment of 25°C and 89.5% RH for 10 weeks.

Banaszek and Siebenmorgen (1990) conducted a study on re-wetting characteristics of long grain variety of rough rice for a limited range of temperatures and relative humidities. They collected the weight data manually, removing the test sample from the conditioned chamber, at different intervals, and only 12 data points for each test. Hacihafızoğlu et al. (2008) investigated the suitability of several drying models available in literature in defining the thin layer drying behaviour of long-grain rough rice by using statistical analysis and found that Midilli et al.'s is the most appropriate model for drying behaviour of thin layer rough rice. They also found that the Page model gives better fit among the two parameter models. Chen and Tsao (1994) used several models to define their experimental data for the thin layer rough rice and concluded that the two-term model gives the best fit among them. Das et al. (2004) showed that the Page model describes the experimental data adequately for drying of high moisture rough rice. Four different thin layer drying models were used by Chen and Wu (2001) to simulate thin layer drying of rough rice with high moisture content and the two term model was found as the best fit in this study. Cihan et al. (2007) found that the most accurate model is the Midilli et al. model in defining the intermittent drying process of rough rice.

Basunia and Abe (1999, 2005) conducted a study on moisture adsorption isotherms and thin-layer re-wetting characteristics of rough rice over a wide range of temperature and relative humidities. They fitted only a single thin-layer drying equation to describe the moisture re-wetting characteristics of rough rice. So, there is need to find out the best fitted equation to describe the rewetting characteristics of medium grain rough rice from low to high temperature which is commonly used in rough rice drying and re-wetting The object of this work is to determine the rate of moisture transfer in re-wetting rough rice over a range of temperature and relative humidity, and to find the most suitable thin-layer re-wetting model for rough rice which could be used in the simulation of moisture transfer during ventilated storage.

MATHEMATICAL EQUATIONS TO PREDICT THIN-LAYER REWETTING

The drying characteristics of rough rice have been examined by many researchers and various models for the prediction of the drying rate have been performed with more or less success. Mathematical modeling of drying is crucial for the optimization of operating parameters and performance improvements of the drying system. The most commonly used thin-layer rewetting or drying models of grain are Diffusion (Newman, 1931), Approximate form of diffusion (Boyce, 1965), Page (Page, 1949), Exponential (Jayas et al., 1991) and Polynomial (Wang, 1978). The following models were therefore chosen for this study to fit the observed rewetting data:

1. Simplifications of the well-known diffusion model for large drying or re-wetting times that is frequently used to

predict the drying and re-wetting of grain is given as:

$$M_R = \frac{M_t - M_e}{M_i - M_e} = C \times \exp\left(-\frac{\pi^2 D t}{R^2}\right) \qquad (1)$$

where $C = 6/\pi^2$, M_R is the moisture ratio, M_t is the moisture content at any time in dry-basis, M_e is the equilibrium moisture content in dry-basis, M_i is the initial moisture content (dry-basis), t is the drying time in hour (h), D is the diffusion coefficient in m^2/h, R is the sphere radius in m.

2. The most commonly used empirical equation to describe the thin-layer drying and re-wetting of cereals is that of Page (Page, 1949):

$$M_R = \exp(-K \times t^N) \qquad (2)$$

Where, t is the re-wetting time in min; and K, N are the re-wetting parameters.

3. Exponential model (Lewis, 1921) can be written as:

$$M_R = \exp(-K \times t) \qquad (3)$$

Where, t is the re-wetting time in min, K is the re-wetting parameters.

4. Approximate form of diffusion equation (Boyace, 1965) for thin layer-drying or rewetting can be written as

$$M_R = a \exp(-K \times t) \qquad (4)$$

Where, a is product dependent constant, t is the re-wetting time in min; and K is the re-wetting parameter.

5. Second order polynomial equation (Thompson et al., 1968; Wang and Singh, 1978) is of the from:

$$M_R = a + b\,t + c\,t^2 \qquad (5)$$

Where, t is the re-wetting time in min, a is the product dependent constant and b, c are the re-wetting parameters.

MATERIALS AND METHODS

The range of re-wetting conditions for the experiment is presented in Table 1. The procedure to determine weight data of the sample in the thin-layer rewetting and the adsorption equilibrium moisture content were described elsewhere (Basunia and Abe, 1999, 2005). Thin-layer re-wetting characteristics of rough rice were determined at temperature ranging from 17.8 to 45°C and for relative humidities ranging from 56 to 89.3%, with initial moisture contents in the range of 10.26 to 12.71% dry-basis. The data of sample weight, and dry and wet bulb temperatures of the re-wetting air were recorded continuously throughout the re-wetting period for each test of 25 tests. The re-wetting process was terminated when the moisture content change in 24 h was less than 0.1% dry-basis (weight change was less than 0.05 g). Normally, such an experiment lasted for 4 to 6 days. The final points were recorded as the dynamic equilibrium moisture contents. Each data file consisted of more than 300 measured points.

Re-wetting parameters of each of the models were found for each test run using linear regression. The coefficients of determination R^2 were all above 0.90. The 25 sets of values for different parameters were used in a multiple regression procedure to find expressions for each parameter of the model equations. The measured and simulated moisture contents were compared and statistically analyzed for determining the best fit equation. The standard error of estimate (SEE) indicates the fitting ability of a model to a data set. The smaller the SEE value, the better the fitting ability of an equation. For the same data set, the equation giving the smallest SEE value represents the best fitting ability (Basunia and Abe, 1999, 2001). The standard error of estimate (SEE) is expressed as:

$$SEE = \sqrt{\frac{\sum_{i=1}^{m} (M_t - M_s)^2}{df}}$$

Where M_s is the measured moisture content in dry-basis and df is the degree of freedom. For large data set, as in this experiment, it is defined as:

$$SEE = \sqrt{\frac{\sum_{i=1}^{m} (M_t - M_s)^2}{m}}$$

where m is the number of data points.

RESULTS AND DISCUSSION

Expressions for the parameter of model Equation (1)

The values of the parameters C and diffusivity D of Equation (1) were obtained by linear regression analysis. It was observed that C varies between 0.802 to 0.892 within the temperatures and relative humidities studied. Hence, for analysis and interpretations of the results, an overall average value of C from all tests was used. The average value of C for 25 tests was 0.848. This effectively assumes C to be a product-dependent constant instead of 0.608 for a perfectly spherical grain kernel as in Equation (1). Table 1 shows the values of D and the corresponding values of standard error of estimate (SEE) values of moisture content of all tests when the parameter C was fixed at this overall average of 0.848. The average SEE value of 25 tests was only 0.121% dry-basis for a fixed value of $C = 0.848$. The assumption, therefore, of taking C as a product-dependent constant seems valid for representing the re-wetting rate data of rough rice. The expression relating diffusivity, D in m^2/h, and re-wetting air temperature, T in °C, was found as:

Table 1. List of the experimental conditions, and standard errors of estimate (SEE) for each test.

Re-wetting conditions		Initial moisture content	Diffusion model	Page Model	Exponential	Approximate form of diffusion	Polynomial
T(^{0}C)	R_H	(%db)	(%db)	(%db)	(%db)	(%db)	(%db)
17.8	72.1	10.30	0.164	0.241	0.708	0.967	0.366
17.8	72.3	12.71	0.157	0.143	0.414	1.093	0.386
21.9	69.1	11.08	0.108	0.216	0.204	0.140	0.312
21.9	80.6	11.04	0.127	0.143	0.184	0.386	0.328
21.9	89.3	11.04	0.129	0.293	0.204	0.382	0.391
25.8	56.0	11.31	0.090	0.118	0.062	0.097	0.390
25.8	62.8	11.38	0.072	0.127	0.108	0.066	0.363
25.8	69.5	11.60	0.074	0.162	0.169	0.063	0.394
25.8	79.4	11.24	0.126	0.112	0.292	0.173	0.326
25.8	88.7	11.31	0.125	0.126	0.475	0.234	0.311
30.2	61.0	11.11	0.031	0.070	0.094	0.046	0.438
30.2	69.0	11.02	0.102	0.192	0.189	0.106	0.565
30.2	80.0	10.96	0.112	0.278	0.238	0.106	0.311
30.2	88.3	11.01	0.213	0.143	0.216	0.175	0.420
35.5	64.7	10.54	0.128	0.157	0.165	0.098	0.309
35.5	70.8	11.79	0.040	0.048	0.148	0.056	0.150
35.5	79.1	11.90	0.068	0.137	0.079	0.146	0.158
35.5	86.9	11.73	0.112	0.170	0.157	0.150	0.321
40.2	68.6	11.31	0.055	0.055	0.151	0.120	0.192
40.2	70.2	10.69	0.065	0.117	0.116	0.470	0.149
40.2	80.0	10.26	0.146	0.157	0.233	0.196	0.409
40.2	88.2	12.08	0.222	0.168	0.143	0.318	0.312
45.0	61.5	10.32	0.094	0.078	0.033	0.049	0.099
45.0	71.7	10.30	0.128	0.059	0.212	0.212	0.453
45.0	77.4	10.40	0.062	0.045	0.173	0.207	0.378
			Average = 0.121	Average = 0.142	Average = 0.207	Average = 0.242	Average = 0.329

*SEE of estimate of predicted moisture content with more than 300 observations for each test.

$$D = 10.0599 \times \left(-\frac{6111.24}{T + 273.15} \right) \tag{6}$$

with a coefficient of determination 0.985.

The very low SEE (0.121% dry-basis) shows the accuracy of the model to predict the moisture content at any time during the re-wetting period. The SEE of individual tests is shown in Table 1. The highest SEE was 0.222%, dry-basis and the lowest was only 0.031%, dry-basis.

Expressions for the parameters of model Equation (2)

The multiple regression analysis for K as a function of temperature T in °C and relative humidity R_H in decimal, yielded:

$$K = 0.01627 + 0.000313\ T - 0.021434\ R_H \tag{7}$$

with a coefficient of determination R^2 of 0.951.

The regression analysis for N as a function of temperature T in °C and relative humidity R_H in decimal, yielded:

$$N = 0.40441 + 0.00248\ T + 0.34959\ R_H \tag{8}$$

with a coefficient of determination R^2 of 0.97.

The highest SEE was 0.293%, dry-basis and the lowest was only 0.045%, dry-basis. The average standard error of estimate between the measured and predicted values of moisture contents for the full data set was only 0.142%

dry-basis. This very low SEE (0.00142) shows the accuracy of the model to predict the moisture content at any time during the re-wetting period. The SEE of individual tests are shown in Table 1.

Expression for the parameter of model equation (3)

The multiple regression analysis for K as a function of temperature T in °C and relative humidity R_H in decimal, yielded:

$$K = -0.00267 + 0.000095 \times T + 0.00186 \times R_H \quad (R^2 = 0.95) \qquad (9)$$

The average standard error of estimate between the measured and predicted values of moisture contents for the full data set was 0.207% dry-basis which is higher than the Page and Diffusion models. The SEE of individual tests are shown in Table 1. The highest SEE was 0.708%, dry-basis and the lowest was only 0.033%, dry-basis.

Expression for the parameter of model equation (4)

The multiple regression analysis for K as a function of temperature T in °C and relative humidity R_H in decimal, yielded:

$$K = 0.00112 - 0.00008\,\mathrm{T} + 0.00010\,R_H \qquad (10)$$

with a coefficient of determination R^2 of 0.91.

It was observed that a varies between 0.832 to 0.931 within the temperatures and relative humidities studied. Hence, for analysis and interpretations of the results, an overall average value of a from all tests was used. The average value of a for 25 tests was 0.866. The highest SEE was 1.093%, dry-basis and the lowest was only 0.046%, dry-basis. The average standard error of estimate between the measured and predicted values of moisture contents for the full data set was 0.242% dry-basis which is higher than the Page and the Diffusion models.

Expressions for the parameters of model equation (5)

The multiple regression analysis for b as a function of temperature T in °C and relative humidity R_H in decimal, yielded:

$$b = 0.00165 - 0.000062 \times T - 0.00088 \times R_H \qquad (11)$$

with a coefficient of determination R^2 of 0.90.

The regression analysis for c as a function of temperature T in °C and relative humidity R_H in decimal, yielded:

$$c = -9.957E\text{-}07 + 3.81E\text{-}08 \times T + 2.14E\text{-}07 \times R_H \qquad (12)$$

with a coefficient of determination R^2 of 0.87.

It was observed that a varies between 0.806 to 0.932 within the temperatures and relative humidities studied. Hence, for analysis and interpretations of the results, an overall average value of a from all tests was used. The average value of a for 25 tests was 0.843. The highest SEE was 0.565%, dry-basis and the lowest was 0.099%, dry-basis (Table 1). The average standard error of estimate between the measured and predicted values of moisture contents for the full data set was 0.329% dry-basis which is higher than the Page and Diffusion models. The SEE of individual test is shown in Table 1. From Table 1, it can be observed that for most of the tests, SEE was below 0.15% dry-basis both by the Diffusion and Page models. It was found that the numerical difference between the moisture contents predicted by Equation (1), and with diffusivity D calculated with Equation (6) and the observed moisture content did not exceed 0.4% dry-basis points in any test conducted at all temperature and relative humidity combination.

Similarly, it was found that the numerical difference between the moisture contents predicted by Equations (2), (7) and (8) and the observed moisture content did not exceed 0.45% dry-basis points in any test conducted at all temperature and relative humidity combination. This amount of error can be accepted for most practical purpose when working with biological products. So Equations (1) and (6) or the Equations (2), (7) and (8) can be used in a deep bed drying simulation model to predict the re-wetting under high ambient relative humidity conditions. The moisture contents simulated by Equation (1) with C = 0.848, and diffusivity D with Equation (6), were compared to observe moisture contents in Figures 1 and 2. The measured and predicted values were in very good agreement. Similar agreements were also observed in other re-wetting conditions. The moisture simulated by Equation (2) with K and N calculated with Equations (7) and (8), respectively, were compared to observe moisture in Figures 3 and 4. The predicted and observed values were in good agreement. Similar agreements were also observed in other re-wetting conditions.

Conclusions

The re-wetting rates of rough rice from low to high

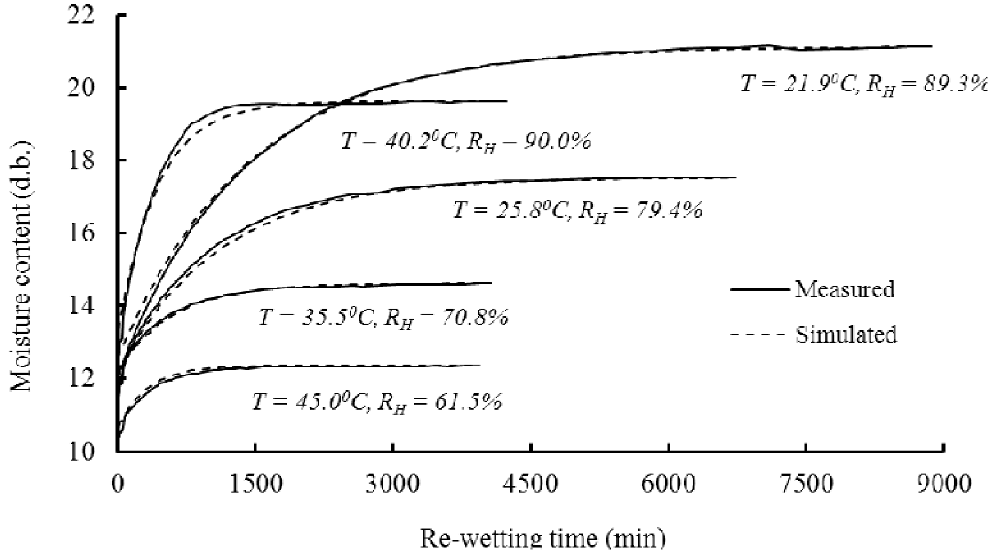

Figure 1. Comparison between the curves predicted by the diffusion model with the values of the diffusivity with Equation (6) and the experimental points at temperature (T) of 21.9, 25.8, 35.5, 40.2 and 45°C, and various relative humidities (R_H).

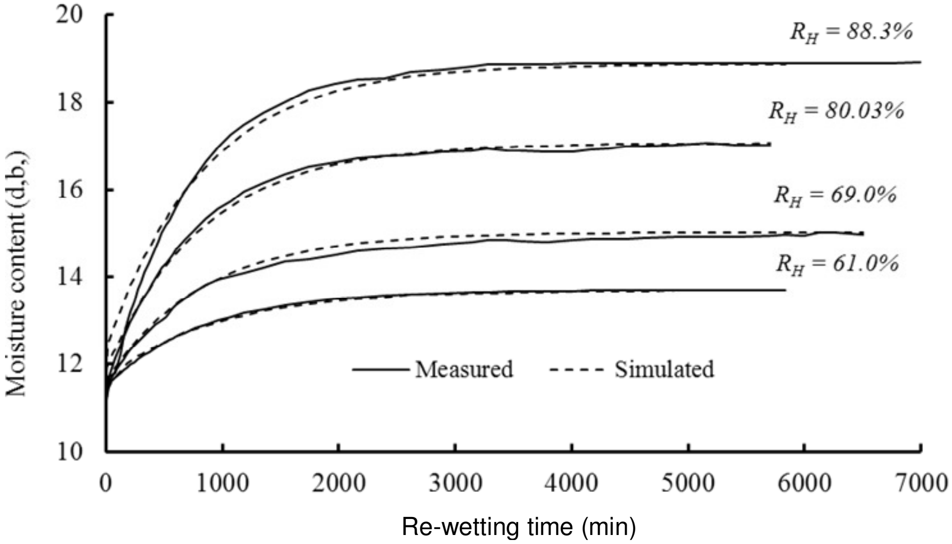

Figure 2. Comparison between the curves predicted by the diffusion model with the values of the diffusivity with Equation (6) and the experimental points at temperature (T) of 30.2°C, and various relative humidities (R_H).

temperatures have been determined. Five models were compared based on standard error of estimate (SEE) values. The Diffusion model and the page model, based on the ratio of the difference between the initial and final moisture content and the equilibrium moisture content, fits the data well with a standard error of 0.121% dry-basis and 0.142% dry-basis, respectively. The Diffusion model and the Page model are found to be the most appropriate models for representing the rewetting characteristics of rough medium grain. Other three models, the Approximate form of diffusion, the Exponential and the Polynomial did not fit well compared to the Diffusion and the page model. The values of SEE for the Exponential, the Approximate form of diffusion

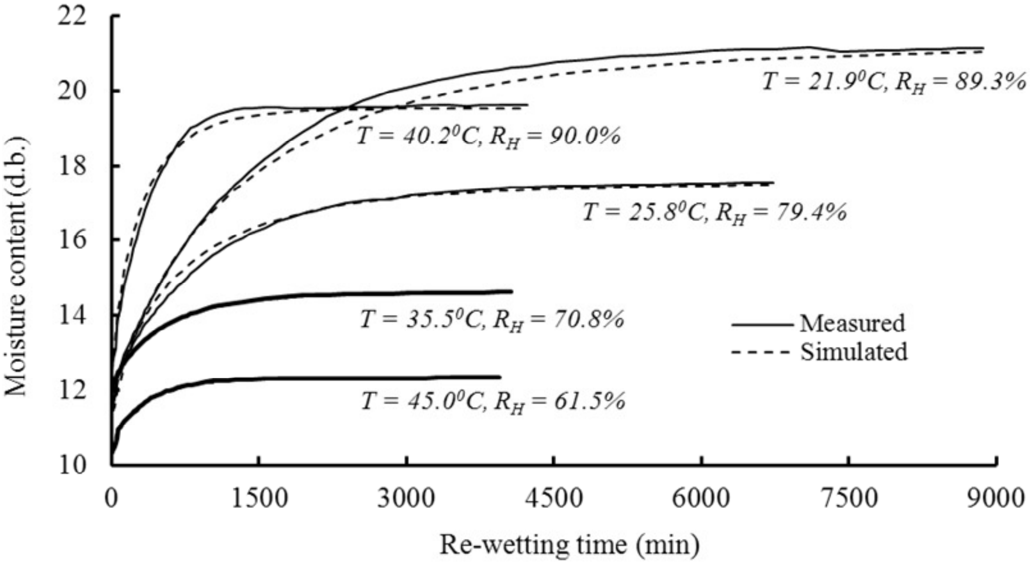

Figure 3. Comparison between the curves predicted by the Page model with the values of the re-wetting parameters with Equations (7) and (8) and experimental points at temperature (T) of 21.9, 25.8, 35.5, 40.2 and 45.0℃, and various relative humidities (R_H).

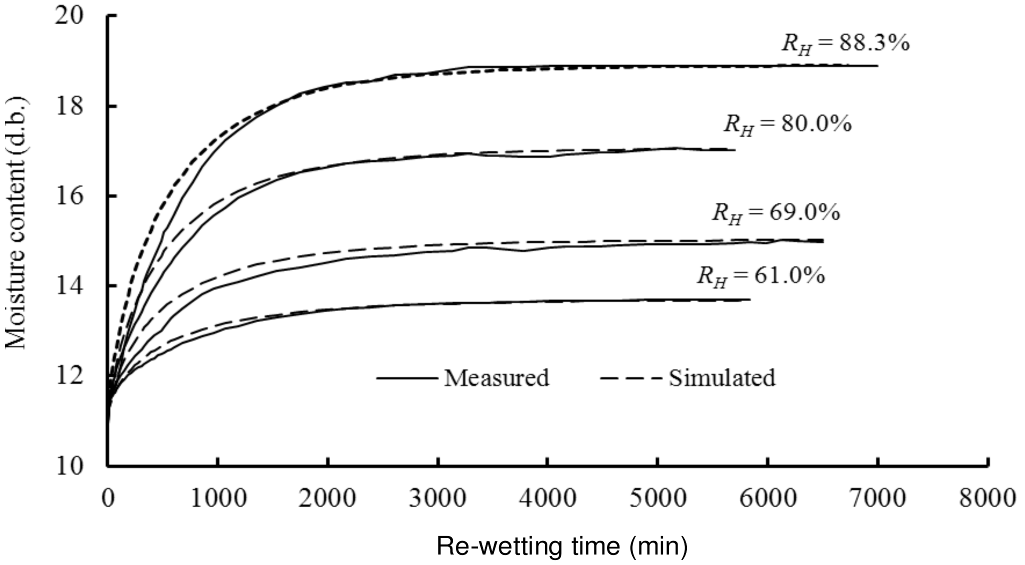

Figure 4. Comparison between the curves predicted by the Page model with the values of the re-wetting parameters with Equations (7) and (8) and experimental points at temperature (T) of 30.2℃, and various relative humidities (R_H).

and the Polynomial models were 0.207, 0.242, and 0.329% d.b., respectively. The result presented here, over a typical 5 day re-wetting period, are useful in the longer term moisture transfer process occurring during ventilated storage.

Notation: ***a,*** Product dependent constants in Equations (4) and (5) respectively; ***b, c,*** re-wetting parameters in Equation (5); ***C,*** product dependent constant in Equation (1); ***K, N***, re-wetting parameters in Equations (2) to (4); M_e, equilibrium moisture content of grain (d.b.); M_i, initial moisture content of grain (d.b.); ***M_t***, moisture content of grain at any time, dry-basis (d.b.); ***M_s***, simulated moisture content of grain at any time, dry-basis (d.b.); ***R,*** radius of the sphere; ***R^2***, coefficient of determination; ***R_H***, relative humidity; ***M_R***, moisture ratio; ***t,*** re-wetting time (hr in Equation 1, and min in Equations (2) to (4); ***T,*** re-wetting temperature (℃).

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