World Academy of Science, Engineering and Technology
International Journal of Agricultural and Biosystems Engineering
Vol:6, No:12, 2012

Predictability of the Two Commonly Used Models to Represent the Thin-layer Re-wetting Characteristics of Barley

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Abstract**—**Thirty three re-wetting tests were conducted at different combinations of temperatures (5.7- 46.3^{0}C) and relative humidites (48.2-88.6%) with barley. Two most commonly used thin-layer drying and rewetting models i.e. Page and Diffusion were compared for their ability to the fit the experimental re-wetting data based on the standard error of estimate (SEE) of the measured and simulated moisture contents. The comparison shows both the Page and Diffusion models fit the re-wetting experimental data of barley well. The average SEE values for the Page and Diffusion models were 0.176 % d.b. and 0.199 % d.b., respectively. The Page and Diffusion models were found to be most suitable equations, to describe the thin-layer re-wetting characteristics of barley over a typically five day re-wetting. These two models can be used for the simulation of deep-bed re-wetting of barley occurring during ventilated storage and deep bed drying.

Keywords**—**Thin-layer, barley, re-wetting parameters, temperature, relative humidity.

I. INTRODUCTION

BOTH the thin-layer drying and rewetting equations are equally important when developing models for the simulation of deep bed drying and aeration of grain. The lower layer of grain desorbs moisture while the upper layer of grain adsorbs moisture in the early stage of deep bed drying. Thin-layer moisture transfer equations are used in deep bed grain drying and re-wetting simulation models. The validity of the deep bed drying or re-wetting model is therefore mostly depend on how accurately the thin-layer drying and re-wetting equations used in the model represent the thin-layer moisture transfer characteristics of the particular grain. Moreover, the grain is exposed to fluctuating air temperatures and relative humidities causing drying and re-wetting cycles in low temperature drying. Reference [1] mentioned that the moisture adsorbing environments can exist in the field before harvesting and subsequently during harvesting, holding, transport, drying and storage of farm crops

Most of the earlier studies [2]-[7] on thin-layer moisture transfer characteristics were conducted with thin-layer drying of cereal grains or oilseeds for a short duration and very little work was done on thin-layer re-wetting barley. It was found that the drying rate of wheat, barley and canola changes as a result of re-wetting [8].

A study [2] was conducted on thin-layer re-wetting and moisture adsorption isotherms characteristics of barley 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 barley. So there is need to find the ability of the two most commonly used models to fit the experimental rewetting data in order to describe the rewetting characteristics of barley from low to high temperature.

Mathematical equations to predict thin-layer rewetting of barley

The most commonly used thin-layer rewetting or drying models of grain are Diffusion [9] and Page [10] models.
The following two models were therefore chosen for this study to fit the observed rewetting data of barley.

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

$$M_R = \frac{M_t - M_e}{M_e - M_i} = \exp\left(-K \times t^{N}\right) \tag{1}$$

where, 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 re-wetting time in min; and K, N are the re-wetting parameters.

(2) Simplifications of the well-known diffusion model for large drying or r-wetting times that is frequently used to predict the drying and re-wetting of grain is given as:

$$M_R = C \times \exp\left(-\frac{\pi^2 D t}{R^2}\right) \tag{2}$$

where, $C = 6/\pi^2$, t is the drying time in hour (h), D is the diffusion coefficient in m^2/h, R is the sphere radius in m.

II. MATERIALS AND METHODS

The procedure to determine weight data of the sample in thin-layer rewetting, and adsorption equilibrium moisture content of barley were described elsewhere [2]-[3]. Thin-layer

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re-wetting characteristics of barley were conducted at temperatures ranging from 5.7 to 46.3°C and for relative humidities ranging from 48.2% to 88.6%, with initial moisture contents in the range of 10.26 to 11.54% 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. 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 4-6 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 the models were found for each test run using linear regression. The coefficients of determination R^2 were all above 0.90. The 33 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 smallest the SEE value, is the better the fitting ability of an equation. For the same data set, the equation giving the smallest average SEE values represents the best fitting ability.

III. Results and Discussions

A. Expressions for the parameter of Model Equation (1) (Page Model)

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

$$K = -1.08 \times 10^{-3} + 1.05 \times 10^{-5}\, T + 1.58 \times 10^{-3}\, R_H \quad (3)$$

with a coefficient of determination R^2 of 0.896.

It was found that N varies between 0.882 - 0.978 with in the temperatures and relative humidities studied. Hence for analysis and interpretations of the results, an overall average value of N from all tests was used. The average value of N for 33 tests was 0.952. This effectively assumes N to be a product-dependent constant. The average SEE value of 33 tests was only 0.176% dry-basis for a fixed value of N = 0.952. The assumption, therefore, of taking N as a product-dependent constant seems valid for representing the re-wetting rate data of barley.

The highest SEE was 0.36%, dry-basis and the lowest was only 0.031%, dry-basis. The average standard error of estimate between the measured and predicted values of moisture contents for the full data set was only 0.176% dry-basis. This very low SEE (0.00176) shows the accuracy of the model to predict the moisture content at any time during the re-wetting period.

B. Expressions for the Parameter of Model Equation (2)(Diffusion Model)

It was found that C varies between 0.888 - 0.994 within the ranges of 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 33 tests was 0.957. This effectively assumes C to be a product-dependent constant instead of 0.608 for a perfectly spherical grain kernel as in equation (2). The average SEE value of 33 tests was only 0.199% dry-basis for a fixed value of C = 0.957. The expression relating diffusivity, D in m^2/h, and re-wetting air temperature, T in ^{0}C, was found as:

$$D = 2.2554 \times 10^{-3} \exp\left(-\frac{4724.32}{T + 273.15}\right) \quad (4)$$

The very low SEE (0.199% dry-basis) shows the accuracy of the model to predict the moisture content at any time during the re-wetting period. The highest SEE was 0.473%, dry-basis and the lowest was only 0.034%, dry-basis.

It was observed that for most of the tests, SEE was below 0.20% dry-basis both by the Page and Diffusion models. It was found the that the numerical difference between the moisture contents predicted by equation (1), and with parameter K calculated with equation (3) and the observed moisture content did not exceed 0.6% dry-basis points in any test conducted at all temperature and relative humidity combination.

Also, it was found the that the numerical difference between the moisture contents predicted by equation (2), with diffusivity calculated with equation (4) and the observed moisture content did not exceed 0.7% 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 the equations (1) and (3) or the equations (2) and (4) can be used in a deep bed drying simulation model to predict the re-wetting under high ambient relative humidity conditions.

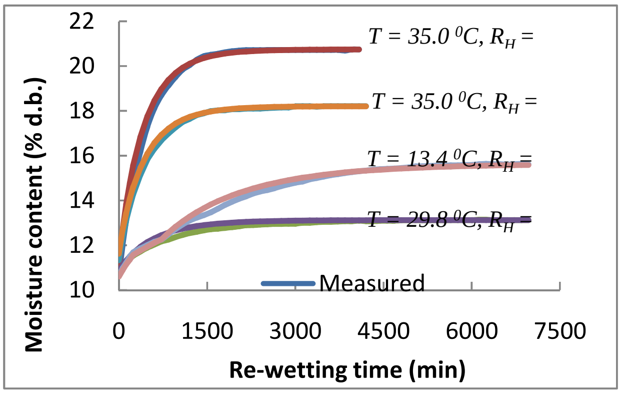

Fig. 1 Comparison between the curves predicted by the Page model with the values of the re-wetting parameter K with equation (3) and N = 0.952 and experimental points at temperature (T) of 13.4, 29.8 and 35.0^{0}C, and various relative humidities (R_H)

The moisture simulated by equation (1) with N = 0.952 and K calculated with equation (3) were compared to observe moisture in Fig. 1. The predicted and observed values were in good agreement. Similar agreements were also observed in other re-wetting conditions. The moisture contents simulated by equation (2) with C = 0.957, and moisture diffusivity D with equation (4) were compared to observe moisture contents in Fig. 2. The measured and predicted values were in very good agreement. Similar agreements were also observed in other rewetting conditions.

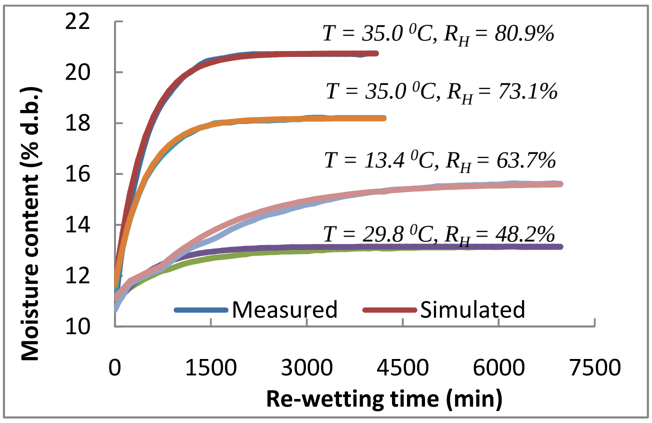

Fig. 2 Comparison between the curves predicted by the diffusion model with the values of the diffusivity with equation (4) and the experimental points at temperature (T) of 13.4, 29.8 and 35.0^{0}C, and various relative humidities (R_H)

IV. Conclusion

The re-wetting rates of barley from low to high temperatures have been determined. It was observed that a considerably re-wetting time and data points are required to obtain a smooth rewetting curve. Two models, the Page model and the Diffusion, were compared based on the average standard error of estimate (SEE) of the measured and predicted values of moisture contents. The Page and the Diffusion models fit the data well with a standard error of 0.176% dry-basis and 0.199% dry-basis, respectively. Both the models are found to be the most appropriate models for representing the rewetting characteristics of barley. The result presented here, over a typical five day re-wetting, are useful in the longer term moisture transfer process occurring during deep bed drying and ventilated storage.

Acknowledgment

The author is greatly acknowledge the financial support of Ehime University, Japan to conduct this research, and also, Sultan Qaboos University, Oman to support financially and providing leave to present this paper in International Conference on Agricultural and Bio-systems Engineering, ICABE 2012 - WASET, Perth, Australia, December 6-7, 2012.

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