Simulation of Low Temperature Rough Rice Drying and Rewetting in Shallow Beds

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Abstract. *Equilibrium simulation model was used for estimating the drying and rewetting of long-grain rough rice in shallow beds due to forced aeration. Limitations of the simulation model were examined for the relative influences of grain layer thickness, time step, and airflow rate on predicted moisture content profiles in grain beds. A value of grain dry matter-to-air ratio equal to or greater than 0.27 based on 1-h time step was determined to yield close agreement between experimental and simulated moisture content profiles. Under such conditions, the simulated moisture content profiles were insensitive to the changes either in layer thickness or time step for a fixed value of grain dry matter-to-air ratio based on 1-h time step. Results showed that equilibrium model predicted rough rice drying and rewetting in shallow-beds reasonably well when the developed criterion for grain dry matter-to-air ratio was applied in the simulation scheme.* ***Keywords.*** *Rice drying, Rewetting, Drying simulation, Equilibrium simulation model.*

A significant portion of the rice grown in the United States is dried and aerated in storage bins using natural air. There has been considerable concern regarding quality changes in beds of rough rice due to moisture adsorption during continuous aeration. Aerating with cool, humid air may cause rewetting of grain especially in the layers near the bottom of the bin (McNeal, 1957). Rewetting of rice during storage is undesirable because the milling quality of grain can be adversely affected (Kunze and Prasad, 1978; Siebenmorgen and Jindal, 1986) and may lead to storage problems such as spontaneous heating, mold development, and insect infestation (Schroeder and Calderwood, 1972). Often it is of interest to know the amount of grain affected for estimating the reduction in head rice yield during the rewetting of rice.

Computer simulation models developed on the assumption of equilibrium conditions between grain and air at the end of a time step have been shown to provide reasonable prediction of moisture content (m.c.) profiles in grain beds for low temperature drying with natural air. The experimental validation of these models has generally been carried out using long duration drying data for grains usually with high initial m.c. As a result, the need for accurately determining the moisture transfer rates between grain and air during relatively short periods of high humidity, especially in shallow depths, still exists.

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Objectives

The purpose of this study was to assess the equilibrium model as a means of simulating low temperature drying and rewetting in rice beds. Therefore, the following were the main objectives:

- Develop a criterion that could be used to define limits for successful application of the thermal and moisture equilibrium assumptions made in the simulation approach.
- Validate the equilibrium simulation model for predicting rough rice drying and rewetting in shallow beds.

Previous Studies

Based on the results of aeration studies in Arkansas, McNeal (1957) reported that the bottom layers in commercial bin drying of rough rice produced lowest head rice yields. He attributed this low head rice yield to over-drying and subsequent moisture absorption during cooling periods. Calderwood et al. (1984) studied the effectiveness and limitations of long-term aeration for maintaining the quality of rice in bulk storage especially in warm and humid climatic conditions. They observed that rice may be successfully stored through periods during which aeration may either increase or decrease the m.c.

Low temperature grain drying simulation models have been reviewed in detail by Sharp (1982). Of all the drying simulation models, equilibrium models developed by Bloome and Shove (1971) and Thompson (1972), and their modified form by Morey et al. (1979) for conditions of low temperature and low airflow, have been extensively used primarily because of their significantly lower computer time requirements in comparison with partial differential equation models developed by Bakker-Arkema et al. (1974).

Several studies have been made to validate equilibrium simulation models using the results of drying experiments

(Sharma and Muir, 1974; Van Ee and Kline, 1979; Morey et al., 1979; Mittal and Otten, 1982). However, experimental data on rewetting of grains are very limited especially in the lower layers of bins where the grain is most affected by changing inlet air conditions. For low airflow rates, the agreement between experimental and simulated results based on equilibrium models are generally good. However, higher airflow rates can result in nonequilibrium conditions between grain and air. Thus wider drying zones than those predicted by the simulation model are required in order to achieve air and grain equilibrium.

Sharma and Muir (1974) observed that experimental drying zones during aeration of wheat and rapeseeds were wider than simulated drying zones indicating that moisture equilibrium was not reached, especially with increasing airflow rates. Mittal and Otten (1982) reported that the equilibrium model of Bloome and Shove (1971) over-predicted the rates of both drying and rewetting in their full-scale experiments with corn. Similar results were also reported by Morey et al. (1979) and Van Ee and Kline (1979). It appears that the assumption of true equilibrium is often not reached in practice especially for grain near the bottom layers of the bin and for relatively high airflow rates. This is suggested by the approach taken by Biondi et al. (1988) who used Thompson's equilibrium model for low airflow rates and Morey's near-equilibrium model for higher airflow rates. No experimental data were given for model validation.

Equilibrium models have been reported to predict drying satisfactorily using large time steps of 3 to 24 h with 10 to 30 layers (Sharp, 1981). If high airflow rates are maintained through shallow beds of grains, equilibrium conditions between the air and grain will not exist. Consequently, the equilibrium models have been modified by incorporating thin-layer drying and rewetting equations to improve the accuracy of their predictions (Morey et al., 1979; Pierce and Thompson, 1979; Van Ee and Kline, 1979; Krueger and Bunn, 1988). The need for using further empirical modifications has also been demonstrated in many studies (Alam and Shove, 1973; Khanna, 1974; Morey et al., 1979; Smith (1984); Krueger and Bunn, 1988).

In general, the major performance features of the equilibrium model can be summarized as follows:

1. The equilibrium model often leads to over-prediction of drying rates since the m.c. of grain in layers near the bottom of a bin does not reach equilibrium with the air when compared with model predictions. Consequently, the moisture removal from each grain layer at every time step needs to be compared with the prediction based on an appropriate thin layer drying equation in order to limit the predicted moisture transfer.
2. Rewetting rates in the lower layers of a bin tend to be overestimated. This is especially true if the equilibrium m.c. of the grain based on desorption isotherms is used with the assumption of no hysteresis, which leads to higher predicted equilibrium m.c. than actually occur (Banaszek and Siebenmorgen, 1990).
3. Use of longer time steps has generally yielded more satisfactory results (Van Ee and Kline, 1979; Morey et al., 1979; Sharp, 1981; Mittal and Otten, 1982).

Despite their limitations and lack of full-scale experimental data required for their validation, Sharp (1981) concluded that equilibrium models provide excellent predictions of grain m.c. during drying.

Model Description and Approach

The equilibrium simulation model developed by Bloome and Shove (1971) and later presented in simplified form by Thompson (1972) was used in this study. The various equations used in the model are as follows:

Energy balance:

$$c_a T_o + H_o(h_{vo} + c_v T_o) + c\, G_o + (H_f - H_o)\, G_o\, c_w = c_a T_f + H_f(h_{vo} + c_v T_f) + c\, T_f \quad (1)$$

Moisture balance:

$$H_f - H_o = (M_o - M_f) R / 100 \quad (2)$$

where

$$R = (\rho_{dm} \cdot x) / (\rho_a \cdot V \cdot t) \quad (3)$$

Equilibrium condition at exhaust from a layer:

$$[ERH]_{grain} = [RH]_{air} \quad (4)$$

where

$$ERH = \exp[(-35.912 / T_f^{0.5}) \cdot \exp(-0.194156\, M_f)] \quad (5)$$

(Sehgal, 1980)

$$RH = P_v / P_s \quad (6)$$

$$P_v = 101325\, H_f / (0.6219 + H_f) \quad (7)$$

(ASAE, 1983)

$$P_s = K \exp[(A + B\, T_a + C\, T_a^2 + D\, T_a^3 + E\, T_a^4) / (F\, T_a - G\, T_a^2)] \quad (8)$$

(ASAE, 1983)

The values of constants in equation 8 are given as follows:

$K = 22{,}105{,}649.25$	$D = 0.12558 \times 10^{-3}$
$A = -27{,}405.526$	$E = -0.48502 \times 10^{-7}$
$B = 97.5413$	$F = 4.34903$
$C = -0.146244$	$G = 0.39381 \times 10^{-2}$

The specific heat of rough rice was calculated using:

$$c_g = 0.3153 + 0.0073\, M_w + 0.0009\, G_o \quad (9)$$

(Suministrado, 1979)

Various thermal properties of air and water were assumed as follows:

Specific heat of water in grain	= 4186 J/kg °C
Specific heat of water vapor	= 1850 J/kg °C
Specific heat of dry air	= 1005 J/kg °C

The latent heat of vaporization of water is given by the equation:

$$h_{vo} = 2{,}502{,}535.259 - 2{,}385.76424\,T \qquad (10)$$

(ASAE, 1983)

In the solution approach, the grain bed was divided into a series of layers. Each layer was subjected to uniform air and grain conditions across and throughout each layer for a selected time step. Air conditions exhausting from a layer were taken as input air conditions to the layer above. Energy and moisture balances were assumed across each layer during the selected time step. Air and grain conditions in the bed were predicted at the end of a time step during drying or rewetting assuming air and grain to have reached thermal and moisture equilibrium and having gone through an adiabatic process. It was also assumed that all processes are reversible and no hysteresis exists between sorption and desorption isotherms.

For any arbitrarily selected grain layer thickness and drying or rewetting time step, equilibrium conditions between grain and air were determined using equations 1 through 4. Knowing the inlet air conditions at any given layer and the initial layer m.c., final air conditions and grain m.c. were calculated at the end of the selected time step. The process was repeated for each layer in the bed at a given time step and the entire procedure repeated for subsequent time steps. Solving these equations is not straight forward but has required special numerical solution techniques (Thompson, 1972). As an alternative, an equation solving software package, TK Solver, was used (Young and Stikeleather, 1989). Equations were entered into a TK Solver rule sheet and solved for unknown variables. Input variables were easily changed to observe their effects on output variables.

Model Limitations

The equilibrium models originally developed by Bloome and Shove (1971) and Thompson (1972) have been modified and improved by several researchers using experimental results. Modified equilibrium models appear to predict grain m.c. profiles reasonably well despite vague guidelines used in selection of time step, number of layers, and upper limits of airflow rates. Despite an inadequacy of these simulations in making realistic predictions near the bottom of bins or in cases of high airflow rates, little attention has been focused on an evaluation of critical limits of applicable airflow rates.

The equilibrium model essentially computes a final m.c. of the grain as a function of dry matter-to-air ratio (R) which itself is fixed indirectly by arbitrary selection of time step, layer thickness, and airflow rate. It is difficult to recognize the contribution of each variable separately in the solution scheme. For a given value of R, the model predicts a final m.c. that may have also been generated with other selections of airflow rates, drying time step, and layer thickness (Thompson, 1972). Thus R plays an important role in the equilibrium simulation model.

It is also implied in these models that increasing airflow rates always lead to lower computed values of final m.c. in the case of drying and higher m.c. values for the case of rewetting. However, these trends cannot be realized in practice. This explains the reason for incorporating thin-layer drying equations in several modified forms of the equilibrium model. In light of these considerations, it becomes necessary to impose a limit on R for obtaining realistic estimates from the simulation model. Table 1 summarizes the values of R used in various grain drying simulation studies.

Inherent to R values in table 1 is the fact that time step and layer thickness were arbitrarily selected based on experience in several studies. As a result, a wide variation in values for R exists. It may be hypothesized that for a given airflow rate, there should be a criterion for defining the range of R within which predicted m.c. are close to experimentally observed values.

Supposing it is possible to fix R using some arbitrarily selected time step, then for any given airflow rate one can determine a required grain layer depth. Under such conditions, a change in airflow would always be accompanied by an automatic adjustment of the layer depth thus compensating for shifts in the m.c. profile. It can also be reasoned that if changes in either layer depth or time step result in automatic adjustments of m.c. profile, then airflow rate is the only remaining factor which must be fixed using an optimum value of R.

Experimental Procedure

An equilibrium model was used to simulate drying in a bed of rough rice with an initial m.c. of 22.0% w.b. and bulk density of 550.2 kg/m^3. Air conditions of 30° C temperature and 50% relative humidity (RH) were used to determine the influence of R, layer thickness, drying time step, and airflow rate on model computations. Airflow rate was assumed to be 0.1 $m^3/s/m^2$ in all simulation runs, giving a R of 0.1359 based on a layer thickness of 0.1 m and drying time step of 1 h.

Laboratory experiments were also conducted to evaluate the effect of various grain and air conditions on R values and resultant model performance in simulating rice drying and wetting. Both multilayer and shallow bed tests were conducted. For multilayer drying tests, a vertical column dryer with seven trays, each having a cross-section of 25 × 25 cm, was used. Each of the seven trays was loaded with about 2 kg of rough rice. The thickness of grain in each tray was about 5.0 cm. Air leaks were prevented by sealing with foam rubber along the sides of the trays. Moisture loss from each tray was determined by periodically removing

Table 1. Grain dry matter-to-air ratios used in equilibrium models for simulation of drying

Study	Grain	Airflow Rate ($m^3/s/m^2$)	Dry Matter-to-air Ratio*
Bloome and Shove (1971)	Corn	0.0254	0.53116
Alam and Shove (1973)	Soybeans	0.0263	0.58083
Sharma and Muir (1974)	Wheat	0.0407	0.28914
Sharp (1981)	Wheat	0.1167	0.21786
Mittal and Otten (1982)	Corn	0.1750	0.05666
	Corn	0.1610	0.06320
Smith (1984)	Barley	0.1043	0.03017

* Based on a 1-h time step.

the trays from the drying unit and weighing with a top loading balance.

In subsequent drying and rewetting in shallow beds, test columns consisting of flanged sections of PVC pipe about 30-cm long and 20 cm in diameter were used. A screen was provided near the bottom of each section. Sections could be joined by bolting to provide grain columns of different heights.

Air was supplied from a storage tank in line with a compressor and its flow rate measured by a rotameter. Air was conditioned by bubbling through a water column. Air temperature and RH were maintained within ±0.5° C and ±1%, respectively.

At the end of a shallow bed test, grain was removed from the test column starting at the top and removing it by layers about 2.5 cm thick. Grain was carefully scooped by hand. Removed grain samples were placed in clear plastic bags and marked as to their respective locations. An average m.c. of different layers in the grain bed was determined the following day by both a single kernel moisture tester (Shizouka Seiki, model CTR-800A) using at least three samples of 200 kernels each and a standard oven method consisting of drying three 25-g samples in a convection oven for 12 h at 130° C (Jindal and Siebenmorgen, 1987). Experimental conditions used in the various tests for rough rice drying and rewetting in shallow beds are summarized in table 2.

Results and Discussion

Effect of Dry Matter-to-Air Ratio

Simulation results presented in figure 1 clearly illustrate that final m.c. in a grain layer depended directly upon the R for fixed inlet air conditions. Assuming grain layer thickness and drying time step to be constant, an increase in airflow rate caused a decrease in the R with a corresponding decrease in the computed value of final m.c. of the grain. For a given layer thickness and time step, the choice of airflow rate leads to marked discrepancies between experimental and simulated results. Data of figure 1 indicate that the relative effects of time step, layer thickness, and airflow rate need to be assessed separately in order to better understand the limitations of model predictions.

Effect of Layer Thickness

An increase in layer thickness led to higher values of R. However, the m.c. profile in a grain bed was not greatly affected by layer thickness. This is illustrated by the simulated results presented in figure 2, which indicate only a slight shift in the bed m.c. profile when layer thickness varied from 5 to 20 cm. Therefore, it can be safely assumed that selection of layer thickness within reasonable limits has minimal effect on simulated m.c. profiles.

Table 2. Test conditions used in rough rice drying and rewetting in shallow beds

Test	Initial MC (% w.b.)	Air Temp. (°C)	Air RH (%)	Airflow Rate ($m^3/s/m^2$)	Bed Depth (cm)	No. of Layers	Tests Duration (h)	R
Drying no. 1*	24.2	23.9	31.5	0.1750	35	7	27	0.2700
Drying no. 2	17.8	24.2	33.5	0.0104	50	10	72	0.6003
Drying no. 3	18.0	30.0	15.2	0.0156	50	10	28	0.4025
Rewetting no. 1	9.2	25.1	88.1	0.0163	60	12	96	0.4131
Rewetting no. 2	9.4	24.0	93.0	0.0076	30	12	48	0.8766
Rewetting no. 3	11.0	20.0	90.0	0.0043	35	7	24	1.1883

* Multilayer test set-up with seven separate trays. All remaining tests were carried out using continuous PVC-test columns.

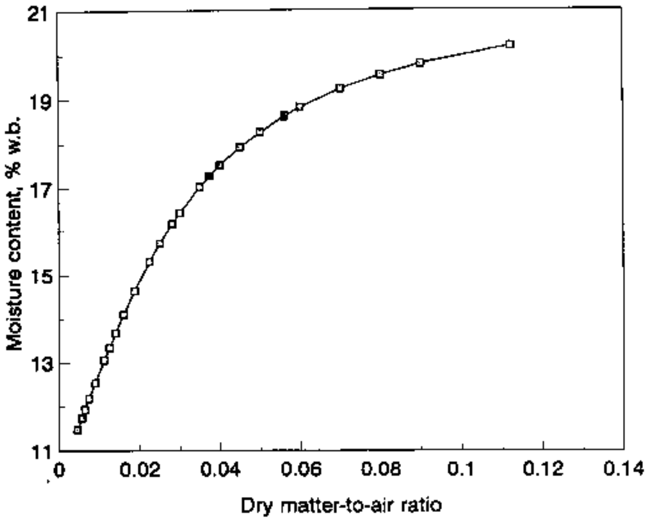

Figure 1–Simulated m.c. of a 0.1-m-thick layer of rough rice as a function of dry matter-to-air ratio (initial m.c. 22.0% w.b.; bulk density 550.2 kg/m³; air temperature 30° C; RH 50%).

Effect of Time Step

An increase in drying time step led to a decrease in R and thus lower values of computed m.c. Figure 3 shows that the effect of drying time step was minimal when considering the change in m.c. over the complete drying duration. Differences in computed values of m.c. were less than 0.5 percentage points and may be considered insignificant based on practical considerations. Over the complete drying duration, shorter drying time steps required more calculations in the computer simulation.

Effect of Airflow Rate

For fixed values of layer thickness and time step, an increase in airflow rate caused a reduction in R. Thus increases in airflow rate resulted in progressively

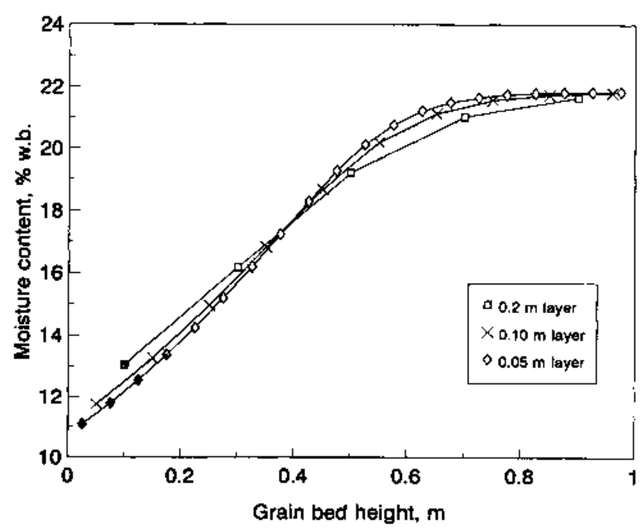

Figure 2–Moisture content profiles in a bed of rough rice when simulating with various layer thicknesses (initial m.c. 22.0% w.b.; bulk density 550.2 kg/m³; air temperature 30° C; RH 50%).

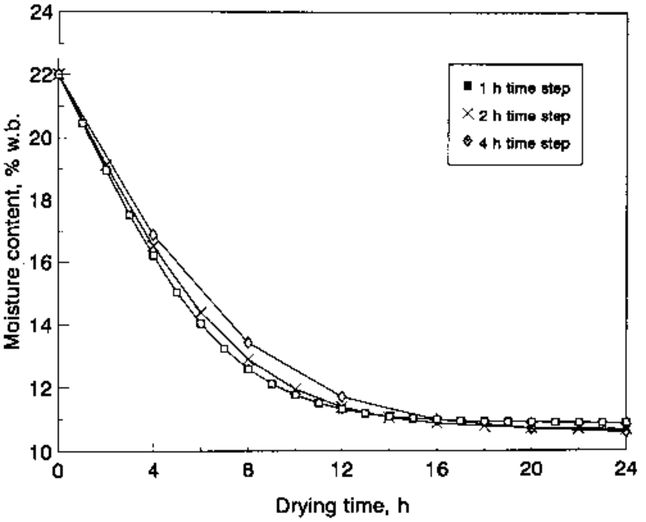

Figure 3–Simulated m.c. of a 0.1-m-thick layer of rough rice as a function of drying time step (initial m.c. 22.0% w.b.; bulk density 550.2 kg/m³; air temperature 30° C; RH 50%; airflow rate 0.1 m³/s/m²).

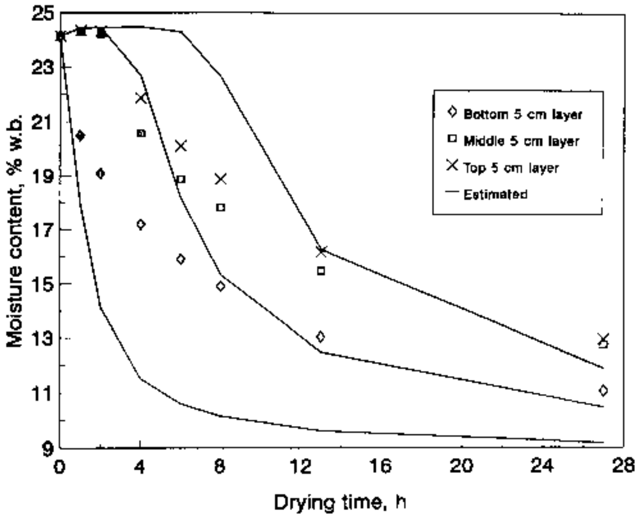

Figure 5–Experimental and simulated m.c. in multilayer drying of rough rice for conditions in test no. 1 shown in table 2.

decreasing final grain m.c. as shown in figure 4 for fixed drying time step and layer thickness. This is in line with an assumption of equilibrium conditions between grain and air made in the simulation model. However, an increase in airflow through the grain layer would not necessarily mean a corresponding increase in the moisture removal rate.

Critical Limit of Dry Matter-to-Air Ratio

Figure 5 presents the experimental and simulated results of a multilayer drying test performed with rough rice. Seven separate trays of rough rice represented a bed depth of about 0.35 m and each layer had a thickness of about 5 cm (table 2, drying test #1). The composite grain column was aerated using a relatively high airflow rate of 0.175 $m^3/s/m^2$. Values of R for each layer were computed for drying durations of 1, 2, 4, 6, 8, 13, and 27 h by taking each duration as a single time step in the simulation model. Results are presented only for the first (bottom), fourth

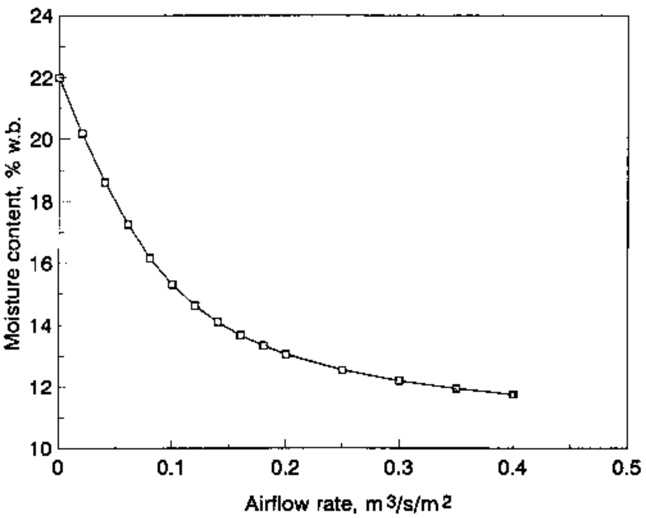

Figure 4–Simulated m.c. of a 0.1-m-thick layer of rough rice as a function of airflow rate (initial m.c. 22.0% w.b.; bulk density 550.2 kg/m³; air temperature 30° C; RH 50%; drying time step 1 h).

(middle), and seventh (top) layers. R values ranged from 0.031535 for the 1-h time step to 0.001168 for the 27-h time step. There were marked differences between predicted and experimental drying curves. In addition to slight rewetting in the upper layers during the initial period of the test, faster drying rates than actually occurred were predicted by the model, especially for the bottom layer. However, these differences in predicted and experimental m.c. appeared to diminish with increasing drying duration.

The assumption of equilibrium conditions made in the model produced results that did not conform to experimental results at this high airflow rate. However, in figure 5 the data indicate that m.c. could be predicted closer to experimental values if a greater R was used. Therefore, predicted m.c. over time was computed by combining individual grain layers in increasing order, thereby increasing the layer thickness and resulting R value. This was equivalent to simulating with layers having thicknesses of 5, 10, 15, 20, 25, 30, and 35 cm. Corresponding R values for composite layers based on a 1-h time step ranged from approximately 0.03 to 0.30. Figure 6 shows the comparison of experimental and predicted m.c. for layer thicknesses of 5, 20, and 35 cm. Though differences in predicted and experimental m.c. existed for the 5- and 20-cm layers, there was a close agreement for the 35-cm layer. These results suggest that it was possible to adjust layer depth to obtain reasonable estimates of m.c. changes with time when using higher airflow rates.

A comparison of the ratio of experimental to predicted m.c. for various layer thicknesses revealed that these ratios fell in a narrow range for different drying durations. The average value of these ratios were plotted against corresponding R values as shown in figure 7. This relationship indicates that predicted m.c. match experimental m.c. (ratio of 1.0) for certain values of R in the simulation model. This critical limit of R was determined by fitting the following equation to the data of figure 7:

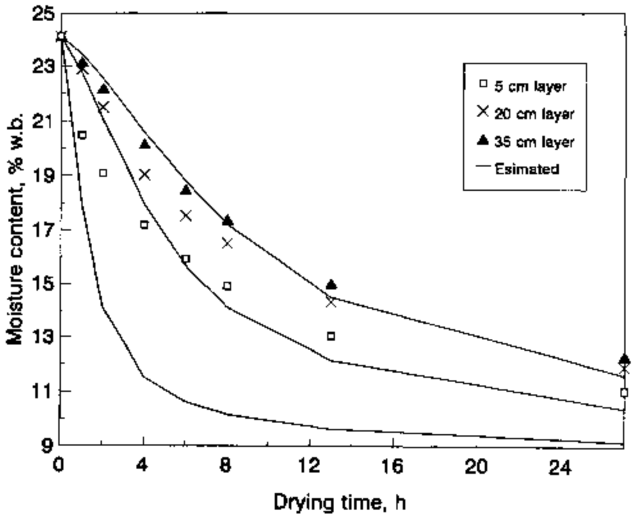

Figure 6–Experimental and simulated m.c. of rough rice in test no. 2 shown in table 2 when selected layers were combined.

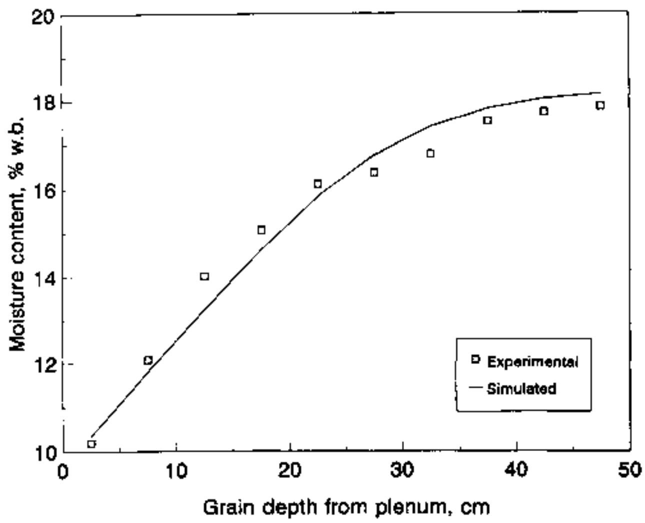

Figure 8–Experimental and simulated m.c. of rough rice in drying test no. 2 shown in table 2.

$$\frac{m.c._{expt}}{m.c._{pred}} = 0.82385\, R^{-0.14808} \qquad (11)$$

$$r^2 = 0.985, SEE = 0.014$$

A value of R was determined to be about 0.27 for a time step of 1 h by matching values of experimental and predicted m.c. However, it is conceivable that a value of R greater than 0.27 could also lead to reasonable predictions of m.c. profiles when low airflow rates are used in the equilibrium simulation model. This is apparently supported for the limited range of experimental data by the exponential shape of the curve in figure 7. Thus it should now be possible to specify a grain layer thickness for any given airflow rate across the bed using the recommended value of R based on a 1-h time step. Drying time steps greater than 1 h may be used subsequently without having any substantial effect on the predicted m.c. profile.

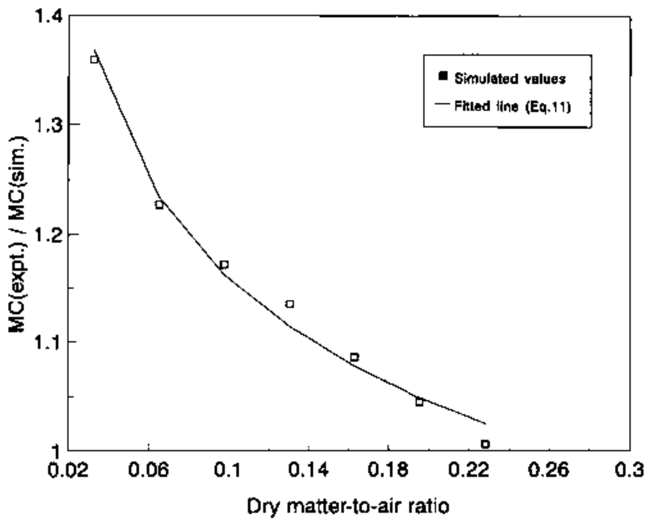

Figure 7–Average values of the ratio of experimental to simulated m.c. of rough rice as a function of dry matter-to-air ratio based on a 1-h time step in multilayer drying test no. 1 shown in table 2. Dry matter-to air ratio was varied by progressively combining grain layers.

Comparison of Experimental and Predicted Drying in Rough Rice Beds

Figures 8 and 9 present the comparison of experimental and predicted m.c. profiles in beds of rough rice for drying tests no. 2 and no. 3, respectively, shown in table 2. These drying tests were conducted using low airflow rates with values of R for test no. 2 and test no. 3 being equal to 0.60 and 0.40, respectively, and based on a 1-h time step. In the computation procedure, a complete drying duration in each experimental test was considered as a single time step and thus applicable values of R for each layer were obtained by dividing the R-values based on a 1-h time interval by the total duration of the test. In both tests there was a close agreement between experimental and predicted m.c. Also there was no need for adjusting layer thickness in the grain bed since hourly values of R well exceeded the critical value of 0.27. These results appeared to support the ideas

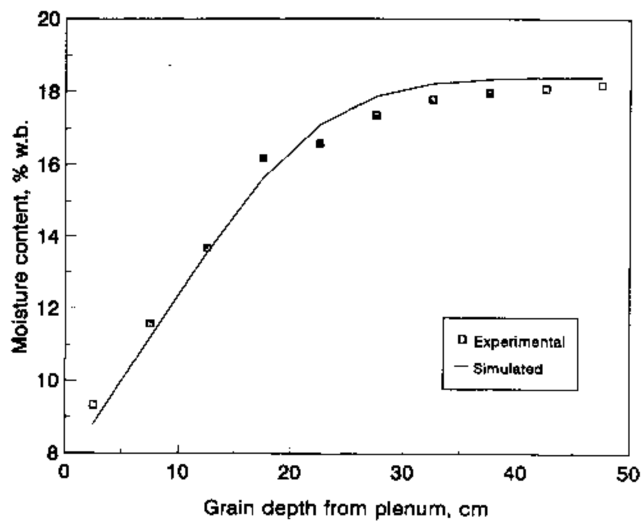

Figure 9–Experimental and simulated m.c. of rough rice in drying test no. 3 shown in table 2.

about a general utility of specifying a limiting value of R for better predictions of m.c. profiles in a grain bed when using the equilibrium model.

Comparison of Experimental and Predicted Rewetting in Rough Rice Beds

Results of rewetting tests for shallow beds of rough rice are presented in figures 10, 11, and 12 corresponding to rewetting test conditions 1, 2, and 3 from table 2. As in the case of drying tests, rewetting tests were also conducted using low airflow rates. Grain layer thickness used in the simulation model ranged from 2.5 to 5.0 cm in all test runs, resulting in R-values of 0.41, 0.44, and 1.19 for the first, second, and third test, respectively. The maximum difference between experimental and predicted m.c. was less than 0.5 percentage points in all three tests and the general shape of the respective m.c. profiles was very similar. There were no consistent differences detected between experimental and predicted m.c. profiles indicating that experimental variation in measured m.c. perhaps was an overriding factor. These results confirmed that the equilibrium simulation approach can be used effectively for estimating m.c. changes in shallow beds of rough rice during aeration with high RH air.

Relationship Between Dry Matter-to-Air Ratio and Airflow Rate

A limiting value of R was determined to be 0.27 in multilayer drying when using a airflow rate of 0.175 $m^3/s/m^2$. It was necessary to combine seven layers into a composite single layer in order to obtain a R value which led to a close agreement between simulated and experimental results. In subsequent drying and rewetting tests, m.c. profiles in grain beds were determined after fixed test durations shown in table 2 which could not be analyzed by the approach used in test no. 1. Instead, a value of R in each drying or rewetting test was determined based on a close agreement between simulated and experimental grain bed m.c. profiles. This enabled an investigation of relationship between R and airflow rate for both drying and rewetting tests as shown in figure 13. It is obvious that R approached a limiting value close to 0.28 with increasing airflow rate, especially beyond 0.2 $m^3/s/m^2$. The following equation represents the relationship in figure 13 adequately:

$$R = EXP(-1.2654 + 0.006788/V) \qquad (12)$$

$$r^2 = 0.931, SEE = 0.143$$

The relationship in figure 13 applies to both drying and rewetting tests, and clearly indicates that R values must be at least 0.28 or higher depending upon the airflow rate

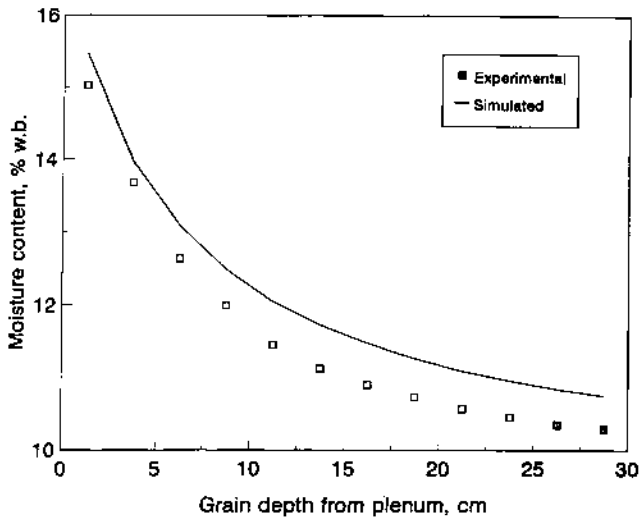

Figure 11–Experimental and simulated m.c. of rough rice in rewetting test no. 2 shown in table 2.

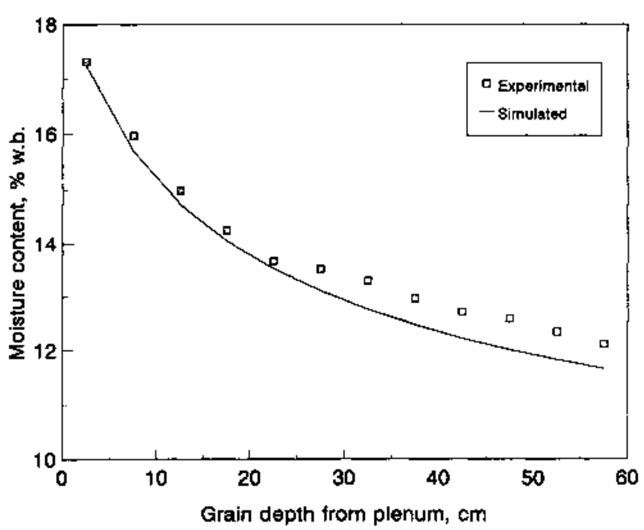

Figure 10–Experimental and simulated m.c. of rough rice in rewetting test no. 1 shown in table 2.

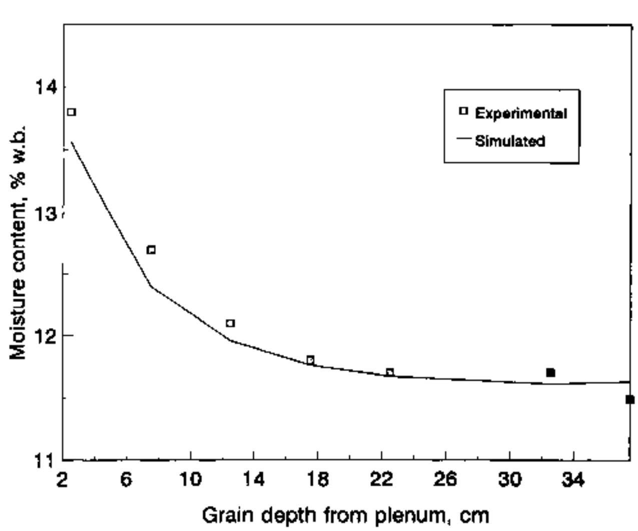

Figure 12–Experimental and simulated m.c. of rough rice in rewetting test no. 3 shown in table 2.

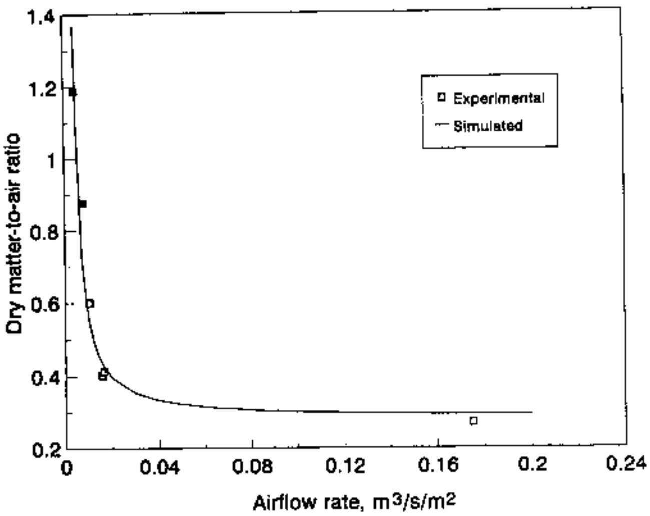

Figure 13–Relationship between grain dry matter-to-air ratio and air flow rate for drying and rewetting of rough rice in shallow beds (layer thickness 5 cm; time step 1 h).

used. Finally, lower values of R resulting from changes in either grain layer thickness or time step can be used in the simulation model provided the selection of R first meets the above developed criterion based on airflow rate.

Summary and Conclusions

In this study limitations of the equilibrium simulation model were examined for estimating drying and rewetting in shallow beds of rough rice during forced aeration. The equilibrium model essentially computes changes in m.c. in terms of R without explicitly accounting for separate contributions of grain layer thickness, time step, and airflow rate across the grain bed. Since various combinations of layer thickness, time step, and airflow rate are possible for a given R, simulation results may be interpreted differently depending upon the selection of these parameters. Results of selected experiments showed that a value of R equal to or greater than 0.27 based on a time step of 1 h should be used in the simulation model for close agreement between experimental and predicted m.c. This implies that grain layer thickness must be specified in the simulation scheme according to airflow rate and time step to have reasonable predictions from the model provided the condition of a limiting value of R based on 1-h time step is first enforced.

Comparison of experimental and simulated test results indicated that the equilibrium model can satisfactorily predict m.c. changes in shallow beds of rough rice due to both desorption and adsorption processes under low temperature conditions when developed criterion for R is applied. This value of R was experimentally determined to be 0.27 or higher for rough rice drying and rewetting tests conducted.

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List of Symbols

- c specific heat of grain multiplied by R (J/kg dry air ° C)
- c_a specific heat of dry air (J/kg ° C)
- c_g specific heat of grain (J/kg ° C)
- c_v specific heat of water vapor (J/kg ° C)
- c_w specific heat of water in grain (J/kg ° C)
- EMC equilibrium moisture content (% w.b.)
- ERH equilibrium relative humidity of grain (decimal)
- G_o initial grain temperature (° C)
- h depth of grain bed (m)
- H_f absolute humidity of air at exhaust from a layer (kg water/kg dry air)
- H_o absolute humidity of air at inlet to a layer (kg water/kg dry air)
- h_{vo} latent heat of vaporization of water at reference temperature (° C) (J/kg)
- m.c. grain moisture content (% w.b.)
- M_f final moisture content after a time step (% d.b.)
- M_o initial moisture content (% d.b.)
- M_w grain moisture content (% w.b.)
- P_s saturation water vapor pressure in air (Pa)
- P_v water vapor pressure in air (Pa)
- R grain dry matter-to-air ratio (kg dry matter/kg dry air)
- R_1 grain-to-air ratio (kg grain/kg dry air)
- RH relative humidity of air, P_v/P_s (decimal)
- T reference temperature (° C)
- T_a absolute temperature of exhaust air (° K)
- T_f air temperature at exhaust from a layer (° C)
- T_o air temperature at inlet to a layer (° C)
- t time increment (h)
- V air flow rate ($m^3/s/m^2$)
- x thickness of grain layer (m)
- ρ_a density of air (kg/m^3)
- ρ_{dm} bulk density of grain dry matter (kg/m^3)