Thin-Layer Drying Characteristics of Thai Rough Rice

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ABSTRACT

Thin-layer drying apparatus was designed, constructed and tested to determine the drying rate of long grain rough rice under tropical conditions. Temperature, relative humidity and flow rate of drying air were accurately maintained in the apparatus and the small changes in weight were recorded during the elapsed drying time. Mathematical models were developed using the instantaneous weight, the weight loss and drying time with temperature, relative humidity, flow rate of drying air and initial moisture content of rough rice as the independent variables. The developed models were compared for both accuracy and computational ease. The best model found in this study is the modified form of the exponential model with the exponent as functions of drying air relative humidity and initial moisture content of rough rice while the coefficient as functions of drying air temperature and initial moisture content of rough rice.

INTRODUCTION

Rough rice is a living organism and is hygroscopic in nature. It gains or loses moisture when the vapour pressure of water outside the grain is higher or lower than that inside the grain. It is different from other grains because it has an outer husk cover and a bran layer present during drying and storage. Therefore the heat and mass transfer processes occurring in rice are different from the other cereal grains.

Harvesting rough rice with high moisture contents ranging from 20-22% wet basis (w.b.) normally results in high yields, less damage and prevents field losses due to dropping and shattering, but it is too high for safe storage. Therefore, rough rice must be dried to approximately 13% to 15% moisture content (w.b.) for storage. Fissures and high temperature gradients will be developed when the rough rice has a high moisture content. Fissures lead to broken grains during milling and reduce the milled rice yield.

In general, the drying rate can be increased by using a higher air temperature. However, high temperature during drying causes some grain quality problems such as cracks in the rice kernel, which reduce the milling quality. Efficient drying of rough rice with minimum damage to the grain is a major concern of the rice industry. It can be improved by an accurate analysis of the drying process. Grain drying processes have been studied by many researchers but few published studies are available on tropical rice varieties under tropical conditions. A deep-bed grain drying process is usually based on the assumption that the bed is composed of a series of thin-layers. The exhaust air conditions from a thin layer are treated as the input air conditions to the layer above and, using mathematical and computer simulation, the moisture and temperature profiles in a deep-bed grain drying process can be predicted. The validity of deep-bed models will depend directly on how well the thin-layer drying equation in the model describes the thin layer process. For this purpose, generalized thin-layer rough rice drying models are needed. The model must be suitable for use at any conditions of temperature, relative humidity, flow rate and initial moisture content of rough rice.

The thin-layer drying process can be divided into two periods: 1) the constant rate period, and 2) the falling rate period. Cereal grains usually do not exhibit a constant rate drying period unless they are harvested in a very immature state or have had water condensed or deposited on their surfaces. This implies that the drying rate decreases continuously during the interval of drying until an equilibrium moisture content is reached. In this report, various mathematical models will be developed for predicting the thin-layer drying rate of long grain rough rice during the falling rate period.

Thin-layer drying is considered by most researchers to be identical with single grain kernel drying. Various mathematical models have been proposed and compared with experimental data:

It has long been accepted that drying phenomena of biological products during the falling rate period are controlled by the mechanism of liquid and/or vapour diffusion. Newman (1931) was the first research worker to apply Fick's diffusion law to the drying of solid materials. Assuming that the drying process is isothermal and the resistance to moisture flow is uniformly distributed throughout the interior of the homogeneous and isotropic material, the kinetics of moisture desorption can be derived as

$$\frac{\partial M}{\partial t} = \nabla \cdot (D \nabla M) \quad \text{(1)}$$

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Assuming that the diffusion coefficient, D, is independent of local moisture content and the volume shrinkage is negligible then Fick's second law can be derived as:

$$\frac{\partial M}{\partial t} = D \nabla^2 M \quad \text{(2)}$$

The analytical solutions of equation (2) for various regularly shaped bodies (rectangular, cylindrical and spherical) can be found in Crank (1975). In a spherical body the moisture content is subject to the following initial and boundary conditions:

$$M(r, t) = M_i, \quad 0 \leq r \leq R, \quad t = 0 \quad \text{(2a)}$$

$$M(r, t) = M_e, \quad r = R, \quad t > 0 \quad \text{(2b)}$$

$$\frac{\partial M}{\partial r} = 0, \quad r = 0, \quad t > 0 \quad \text{(2c)}$$

If the average moisture content is used then the analytical solution is as follows:

$$MR = \frac{M - M_e}{M_i - M_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left\{ - \frac{\pi^2 n^2}{R^2} D t \right\} \quad \text{(3)}$$

Equations (2) and (3) were used by Whitaker and Young (1972) to describe the drying rate of corn. Wang (1978) and Steffe and Singh (1979) used these equations to evaluate the liquid diffusivity of short grain rough rice.

Lewis (1921) presented a film model which assumed that the drying process is isothermal and the controlling resistance is a thin film of solid located right behind the gas-solid interface. The drying rate is proportional to the difference between the average moisture content in the solid material and the equilibrium moisture content, $M_e$:

$$\frac{dM}{dt} = -k(M - M_e) \quad \text{...(4)}$$

If the drying constant, $k$, in equation (4) is independent of $M$ and $M_e$, then the equation may be integrated to yield:

$$MR = \frac{M - M_e}{M_i - M_e} = \exp(-kt) \quad \text{...(5)}$$

This model is also called the exponential or logarithmic model. Westerman, White and Ross (1973) applied this model to study effects of relative humidity on high temperature drying of corn.

Several empirical drying models have been developed for cereal grains. Page (1949) developed a modification of equation (5) of the form:

$$MR = \exp(-kt^N) \quad \text{...(6)}$$

where $k$ and $N$ are empirical coefficients. This equation was used by Agrawal and Singh (1977) in their study of single-layer drying characteristics of short grain rough rice and by Misra and Brooker (1980) to describe the thin-layer drying and rewetting rate of shelled corn.

The objectives of this research were:

1. To obtain laboratory data which accurately describes the thin-layer drying rate of long grain rough rice under various air conditions.
2. To develop a mathematical model for predicting the thin-layer drying rate of long grain rough rice using all the experimental data.
3. To select a mathematical model which will satisfactorily describe the thin-layer drying rate.

**MATERIALS AND METHODS**

**Drying Apparatus**

A schematic drawing of the apparatus is shown in Figure 1. It consisted of an air conditioning unit and a drying section. It was fully instrumented for control and measurement of air flow rate, temperature and relative humidity.

The centrifugal blower was capable of delivering an air flow rate of 0.15 m$^3$/s. The speed of the blower was controlled by an autotransformer. The drying air was forced through a heating, humidifying area and then through the rough rice samples. The air temperature was raised to the desired level by using electrical fin-strip heaters. These were controlled by a PID controller. Humidity of the drying air was adjusted by injecting steam to the humidifying section. Water Heaters were also controlled by a PID controller. A sharp-edged orifice was deemed appropriate for computing the air flow rate through the sample. The pressure drop across the orifice...
plate was measured by a micromanometer. Air velocity was also rechecked by a hot wire anemometer. The relative humidity of air was measured by dry and wet bulb thermometers. Dry and wet-bulb copper-constantan thermocouples junctions were located 4 cm below the sample tray to sense the air conditions just prior to entering the sample tray. The wet bulb wicks were fed from a constant level distilled water reservoir. The temperatures were monitored and recorded continuously with a data logger (Takeda Riken Co., Ltd, Model TR 2721) that printed at 1 min intervals. The accuracy of these measurements was checked using a humidity and temperature meter. The probe of meter (model HN-L18) and indicator (model HN-K) were supplied by Chino Co., Ltd.

The square sample tray had an inside dimension of 26 cm. The sides of the tray were made of sheet metal and the bottom was made of brass mesh. This tray was designed to accommodate a 130 g sample of one grain thickness and could be easily removed and placed on a digital balance where it could be weighed with an accuracy of 0.001 g.

**Sample Preparation**

The long-grain rough rice used in this study was of the RD7 variety. Rough rice was obtained from the Pathum Thani Rice Research Center. Kernels were selected carefully in an attempt to minimize the effect of kernel size. The average length, width and thickness of kernels were 7.3 mm, 2.3 mm and 1.8 mm respectively. Since freshly harvested rough rice at high moisture content could not be obtained for the experiment, dry grain was rewetted. To do this the grain was hand cleaned to remove dockage and dust before conditioning. The grain was spread on a brass tray and sprayed with calculated amounts of distilled water to bring the moisture content up to approximately the desired value. After thorough mixing of the grain, it was stored in closed plastic containers at 5°C for at least 14 days and shaken periodically to establish uniform moisture distribution within the grain kernels and throughout the grain mass.

**Experimental Procedure**

Drying air conditions included velocities, relative humidities and temperatures normally used in both batch and continuous-flow dryers in tropical areas.

Thin-layer drying tests were conducted for each combination of the following parameters:

1. Temperature of drying air (33 - 75°C)
2. Relative humidity of drying air (18 - 80 percent)
3. Initial moisture content of rough rice (20 - 40 percent, dry basis)
4. Flow rate of drying air (0.025 - 0.5 m³/s/m²)

The air conditioning unit was run for at least 1 hour before each experiment began, so that the temperature, relative humidity and air velocity were stabilized. During the experiment they were accurately maintained in the apparatus. The samples were removed from the container and allowed to come to room temperature. Grain moisture content was initially determined by using the standard oven method. About 20 g samples in triplicate were used. Initial moisture content was also checked by an electronic tester. After stabilizing the temperature and relative humidity of the drying air, a 130 g sample was placed in the brass-mesh tray which was then placed in the air stream. The weight loss of samples was periodically measured by electronic balance with an accuracy of 0.001 g. During the initial stages of drying, a measurement was made every 5 min. This time interval was increased as the drying rate decreased. At the end of each drying run the final moisture content was checked by the standard oven method.

**DATA ANALYSIS**

The modified exponential model was written as

\[
MR = \exp(-PtQ) \quad \text{(7)}
\]

This model was linearized in the following manner:

\[
\ln\left(\ln(MR)\right) = \ln p + Q \ln t \quad \text{(8)}
\]

The independent variables chosen for investigation were T, ln(T), T², T³, RH, ln(RH), (RH)², (RH)³, V, ln(V), V², V³, M₁, ln(M₁), M₂, and M³. An exponential function was assumed for P and a polynomial function for Q. The equations are

\[
P = \exp\left[ P_{0} + P_{1}T + P_{2}T^{2} + P_{3}T^{3} + P_{4}\ln T + P_{5}(RH) + P_{6}(RH)^{2} + P_{7}(RH)^{3} + P_{8}\ln(RH) + P_{9}V + P_{10}V^{2} + P_{11}V^{3} + P_{12}\ln V + P_{13}(M_{1}) + P_{14}(M_{1})^{2} + P_{15}(M_{1})^{3} + P_{16}\ln(M_{1}) \right] \quad \text{(9)}
\]

\[
Q = Q_{0} + Q_{1}T + Q_{2}T^{2} + Q_{3}T^{3} + Q_{4}\ln(T) + Q_{5}(RH) + Q_{6}(RH)^{2} + Q_{7}(RH)^{3} + Q_{8}\ln(RH) + Q_{9}V + Q_{10}V^{2} + Q_{11}V^{3} + Q_{12}\ln V + Q_{13}(M_{1}) + Q_{14}(M_{1})^{2} + Q_{15}(M_{1})^{3} + Q_{16}\ln(M_{1}) \quad \text{(10)}
\]

Substituting the expressions for P and Q in equation (8)

\[
\ln\left(\ln(MR)\right) = P_{0} + P_{1}T + P_{2}T^{2} + P_{3}T^{3} + P_{4}\ln T + P_{5}(RH) + P_{6}(RH)^{2} + P_{7}(RH)^{3} + P_{8}\ln(RH) + P_{9}V + P_{10}V^{2} + P_{11}V^{3} + P_{12}\ln V + P_{13}(M_{1}) + P_{14}(M_{1})^{2} + \ldots + P_{16}\ln(M_{1}) \quad \text{(11)}
\]

Equation (11) is a particular case of a general linear regression model which contains a lengthy list of independent variables. This list can be shortened to 7 independent variables and the STEPWISE REGRESSION procedure of SAS (Statistical Analysis System) was used to identify the best set of variables and coefficients of these variables. The models that produced the highest R² values in each group (containing the same number of independent variables) and coefficients were determined and are given in Table 1.
Table 1. Various models to describe thin-layer drying

<table>
<thead>
<tr>
<th>Model</th>
<th>P equation</th>
<th>Q equation</th>
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</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>( P = \exp(-3.108) )</td>
<td>( Q = 0.1817 \ln T )</td>
</tr>
<tr>
<td>Model 2</td>
<td>( P = \exp(-4.844 + 0.04T) )</td>
<td>( Q = 0.1915 \ln M_i )</td>
</tr>
<tr>
<td>Model 3</td>
<td>( P = \exp(-15.219 + 3.2081 \ln T) )</td>
<td>( Q = 0.1626 \ln (RH) + 0.0026 M_i )</td>
</tr>
<tr>
<td>Model 4</td>
<td>( P = \exp(-8.520 + 1.128 \ln T) )</td>
<td>( Q = 0.0869 \ln T + 0.019 \ln RH + 0.0801 \ln M_i )</td>
</tr>
<tr>
<td>Model 5</td>
<td>( P = \exp(-6.0405 + 1.3681 \ln T - 0.6587 \ln M_i) )</td>
<td>( Q = 0.449 + 0.00096 RH + 0.0008 M_i )</td>
</tr>
<tr>
<td>Model 6</td>
<td>( P = \exp(-13.720 - 0.057 T + 4.03 \ln T = 0.1175 \ln RH - 0.487 \ln M_i) )</td>
<td>( Q = 0.464 + 0.0008 M_i )</td>
</tr>
<tr>
<td>Model 7</td>
<td>( P = \exp [2.6426 + 0.2258 RH - 0.0019 (RH)^2 - 3.0865 \ln (RH)] )</td>
<td>( Q = 0.4004 \ln T + 0.00007 (RH)^2 - 0.0741 M_i + 0.0013 (M_i)^2 )</td>
</tr>
</tbody>
</table>

The equation used to calculate the equilibrium moisture content, \( M_e \), for long grain rough rice (RD7) was developed by Laiithong (1987). In all tests, the drying curve tended towards the values of calculated \( M_e \). The equation was:

\[
(1 - (RH)/100) = \exp \left[-4.723 \times 10^{-6} (273 + T) (M_i)^{2.386} \right] \tag{12}
\]

RESULTS AND DISCUSSION

The developed models were compared for both accuracy and computational ease. Finally, an appropriate drying model No. 5 was identified as follows:

\[
M = (M_i - M_e) \exp(-P(Q)) + M_e \tag{13}
\]

\[
P = \exp(-6.0405 + 1.3681 \ln T - 0.6587 \ln M_i) \tag{14}
\]

\[
Q = 0.449 + 0.00096 (RH) + 0.0008 M_i \tag{15}
\]

\[
M_e = \left\{ \begin{array}{ll}
-1 \ln \left(1 - \frac{RH}{100}\right) & \text{if } 1/2.386 \\
4.723 \times 10^{-6} (273 + T) & \text{if } \frac{1}{2.386}
\end{array} \right.
\]

The ranges of independent variables used to develop the above equations are:

- Drying air temperature: \( 33 - 75 \)°C
- Drying air relative humidity: \( 18 - 80 \) percent
- Initial moisture content of rough rice: \( 20 - 40 \) percent, dry basis
- Flow rate of drying air: \( 0.025 - 0.5 \) m³/s/m²

Figures 2 and 3 are a comparison of predicted drying curves with observed experimental data for typical test conditions. Predicted curves were calculated using equation (13) with \( P \) and \( Q \) determined from equations (14) and (15), respectively. Thin-layer drying rates increased with decreasing relative humidity and with increasing temperature. Changes in air flow rate had no effect on the thin layer drying rate.

CONCLUSIONS

The best available model found in this study is the modified form of the Page’s model with the exponent as functions of drying air relative humidity and initial moisture content of rough rice while the coefficient as functions of drying air temperature and initial moisture content of rough rice. The derived empirical model was shown to predict adequately the thin-layer drying rate of long grain rough rice (RD7) over the range of conditions tested. Predictions using the model also compared favourably with experimental drying data, the \( R^2 \) value for the above thin-layer...
drying model for all data being 0.981. The model can be adopted for use with computer based simulation models for deep-bed drying.

REFERENCES


LIST OF SYMBOLS

D = Diffusion coefficient, cm²/hr
M = Local moisture content, dry basis (percent)
M = Average moisture content, dry basis (percent)
M = Equilibrium moisture content, dry basis (percent)
M = Initial moisture content, dry basis (percent)
MR = Moisture Ratio = \( \frac{M - M}{M - M} \)
MR = Average moisture ratio = \( \frac{M - M}{M - M} \)
R = Radius of rice, cm
R² = Coefficient of determination
RH = Relative humidity of drying air, percent
r = Radial distance, cm
T = Drying air temperature, °C
t = time, min
V = Velocity of drying air, m/s

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