Development and Validation of Mass Transfer Model for rough Rice (Sepidrod) Kernel drying

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Abstract
Rapid drying can increase brittleness and induce internal cracks which predispose the product to breakage during subsequent activities. The drying process must be understood and controlled so that design guidelines which reduce or minimize drying damage to rough rice can be established and improved. This study is to give a mathematical model with numerical solution to follow the mass distributions inside a cross sectional area of an individual rough rice (‘Sepidrod’) kernel that it is function of drying time with respect to the effects of the coupled heat and mass transfer processes. The applied drying models are similar to the modified Luikov’s equations Simultaneous heat and mass diffusion in biological materials. This mathematical model can be used for investigating rough rice with different drying characteristics during drying. A finite element formulation and solution of a set of nonlinear coupled conductive heat and diffusive moisture transfer equation to improve grain drying simulation of axisymmetric bodies is presented. Axisymmetric linear triangular elements with two degree of freedom per node are used to discretize the rice grain in both models. The moisture distributions inside the individual rough rice kernels were produced by the model. Good agreement has been observed when the output of nonlinear model was compared to experimental data by others. This comparison showed a no significant statistical difference and Curves of equal moisture inside the grain were plotted during drying.

1 INTRODUCTION

Artificial drying is one of the important stages of rough rice processing. Proper drying procedures eliminate the potential of spoilage during subsequent stage of processing and help to improve the quality of the product. A considerable number of theoretical and experimental studies have been conducted to describe the drying process of grains. Luikov developed a mathematical model for describing the drying of porous media. Some researchers applied this model to grain drying [16]. It concluded that consideration of the coupling effects of temperature and moisture in the analysis of grain drying is not required for engineering practice [10, 11]. Jia et al. combined Luikov’s model and considered the effects of thermal behavior of grain and internal temperature and moisture gradients, which increased the drying simulation accuracy [12]. Sokhansanj and Bruce proposed a model for grain drying which assumed that the liquid form of moisture diffused to the outer boundary of the kernel and evaporated on the surface of the grain [20]. This assumption was supported by wheat drying experiments conducted [4]. However, some assumptions, such as the constant diffusion coefficient and material properties for simplifying calculations, could affect the simulation accuracy.

Although grain drying usually takes place in bulk, it is the individual kernels that interact with the drying medium. The drying behavior, as described by moisture, temperature and stress distributions inside a kernel during drying and the quality traits of individual grain kernels, affect the overall quality of the grain dried in a dryer [23]. Therefore, it is important
to examine the internal behavior of a single grain kernel in order to improve the drying process and product quality. Because of the small size of most grain kernels, internal changes of temperature and moisture conditions are not easily measured. Computer simulation has surfaced as a powerful tool for achieving this goal. The increasing development of special professional software has had a great impact on the design of dryers and the quality evaluation of grains, and made the tedious and time-consuming heat and mass transfer calculations, optimization and quality assessment much easier. Much work has been done to simulate the temperature, moisture content and stress distributions inside single grain kernels [12, 3, 18, 22, 23, 21].

In the current study, a mathematical model describing the mass transfer during rough rice drying is developed. The simulation of rough rice ‘Sepidrod’ variety drying was modified by the experimental data of the thin layer drying.

2 MATERIALS AND METHODS

2.1 Mathematical simulation and experimental verification

2.1.1 Mathematical model

For grain drying simulation, the fick’s diffusive equation describing the mass transfer process has been extensively applied, i.e. (Jia and Sun, 2000).

\[
\frac{\partial X}{\partial t} = \text{div}(DX) \tag{1}
\]

Where X is the moisture content d.b. (kg/kg); D is the diffusion coefficient (m²/s); and t is time (s). In convention drying, the surface of the grain kernel exchanges heat with the environment by convection while the internal one part of the kernel is heated by conduction. If assuming that the moisture diffuses to the outer boundary of the kernel in liquid form and that the evaporation takes place at the surface of the grain, besides Eqn (1), the heat conduction equation for grain should also be given:

\[
\rho c \frac{\partial T}{\partial t} = \text{div}(k\nabla T) + L \rho \frac{\partial X}{\partial t} \tag{2}
\]

Where \( \rho \) is the density (kg/m³); \( c \) is the specific heat (J/kg °K); \( T \) is the temperature (°K); \( k \) is the thermal conductivity (W/m °K); and \( L \) is the latent heat of vaporization of water (J/kg). The corresponding boundary and initial condition for Eqns(1) and (2) are:

\[
D \left( \frac{\partial X}{\partial n} \right) + h_m (X - X_{a}) = 0 \tag{3}
\]

\[
k \left( \frac{\partial T}{\partial n} \right) + h(T_s - T_a) = 0 \tag{4}
\]

\[
t = 0, X = X_0, T = T_0 \tag{5}
\]

where \( h_m \) is the surface mass transfer coefficient (m/s); \( X_{a} \) is the moisture content of the ambient air d.b. (kg/kg); \( h \) is the convection heat transfer coefficient (W/m² °K); \( T_s \) is the surface kernel temperature (°K); and \( T_a \) is the ambient temperature (°K). Because of in this paper, only moisture diffusion in rough rice kernel is studied then model of mass transfer is developed. The components of cylindrical coordinate system are \( \theta \), \( r \) and \( \phi \) that are elongated in the \( Z \) direction so that the new coordinate form egg-shaped surfaces. Equation (1) was rewritten by cylinder coordinate system (Fig. 1).

![Figure 1- Schematic of rough rice kernel with the cylindrical coordinate system](image)

\[
\frac{\partial X}{\partial t} = D \frac{\partial^2 X}{\partial r^2} + \frac{D}{r} \frac{\partial X}{\partial r} + D \frac{\partial^2 X}{\partial z^2} \tag{6}
\]
2.1.2 Finite element analysis

In order to solve Eqn (6), the finite element method is used Eqn (3). Using the variation calculus method, the functions of the partial differential equations Eqn (1) can be written as [13].

Let the dependent variable T be approximated by interpolating functions of the form:

\[
J = \frac{1}{2} \int \left( \frac{\partial}{\partial r} \left( D \frac{\partial X^{(e)}(r,z,t)}{\partial r} \right) - \frac{\partial}{\partial z} \left( D \frac{\partial X^{(e)}(r,z,t)}{\partial z} \right) \right) \frac{\partial}{\partial r} X^{(e)}(r,z,t) + \left( \frac{\partial X^{(e)}(r,z,t)}{\partial z} \right)^2 ds
\]

Based on the finite element method, a single grain kernel can be divided into n triangular elements, and then the minimum values of Eqn (7) are solved:

\[
\frac{\partial J}{\partial [X]} = \sum_{e=1}^{n} \frac{\partial J}{\partial [X]} = 0
\]

The moisture within each element, X^{(e)}, can be approximated by the liner interpolation polynomials, that is the matrix of the shape function, [N^{(e)}], then Eqn (8) was rewritten:

\[
\frac{\partial J}{\partial [X]} = \frac{\partial J}{\partial [X]} [N^{(e)}] + \int h_m(X) [N] ds = 0
\]

Where in simplified forms:

\[
[K][X] + [C] \frac{\partial [X]}{\partial t} = F
\]

Eqn 10 can be expresses in a matrix form:

\[
\begin{bmatrix}
K_{11} & K_{12} & \cdots & K_{1n} \\
K_{21} & K_{22} & \cdots & K_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
K_{n1} & K_{n2} & \cdots & K_{nn}
\end{bmatrix}
\begin{bmatrix}
X_1^{(e)} \\
X_2^{(e)} \\
\vdots \\
X_n^{(e)}
\end{bmatrix} +
\begin{bmatrix}
C_{11} & C_{12} & \cdots & C_{1n} \\
C_{21} & C_{22} & \cdots & C_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
C_{n1} & C_{n2} & \cdots & C_{nn}
\end{bmatrix}
\begin{bmatrix}
\dot{X}_1^{(e)} \\
\dot{X}_2^{(e)} \\
\vdots \\
\dot{X}_n^{(e)}
\end{bmatrix} = F_{M1}
\]

\[
C_{M2} = F_{M2}
\]

Eqn (14) can be further simplified as:

\[
K[X] + C\dot{X} = F = 0
\]

The forward difference method is used to approximate {X}, therefore Eqn (15) is rewritten as:

\[
\left(K + \frac{C}{\Delta t}\right)X^{n+1} = \frac{C}{\Delta t}X^n + F
\]

A computer program for a two-dimensional transient field problem such as the one described by (Eqn) 16 was written by segerlind [19]. The effect of moisture content for each time step it was modified for use of axially symmetric triangular elements. This new program first solves Eqn (16) for given initial nodal values. For every time step, \(\Delta t\) and a given set of nodal values, \([X]\), a set of nodal moisture values \([MX]_{i,1}\), are obtained and stored. Programming Languages is Fortran 90. Computational languages, were used in the development of the software, was Fortran PowerStation 4.0 under Windows XP 2002 platform.

2.2 Sample preparation

‘Sepidrod’ is one of the varieties of rough rice in Iran. This cultivar was used in this study. Before experiment, moisture content of kernels was adjusted to 17% (d.b.) by intermittently adding a calculated amount of distilled water to wheat kernels. Moistened samples were placed in sealed plastic containers and kept for at least 72 h in a cold store at 10°C to allow moisture to distribute inside the kernels while preventing any considerable microbial growth drum [1, 7, 6].
2.3 Thin layer drying data of rough rice kernels

Fig. 1 shows the schematic diagram of the experimental dryer unit that used to determine drying characteristics of rough rice kernel. The equipment used (Fig 2) consisted of a 2kW, 3000min⁻¹ centrifugal fan (9) (maximum flow rate 0.15m³s⁻¹) which drew ambient air from the laboratory and sent it to a tube (6), toward heater that have four (0.6kW) electric resistance (5) whose power could be regulated (1) to attain target drying temperature. The air thus heated was passed toward a duct (3) (internal diameter: 0.3m), and its positive pressure determined using a vertical \( \text{U} \) tube (7) filled with water, with one end open to the atmosphere and then directed toward the drying chamber (2) where the air was passed upward through a 0.3m internal diameter mesh-bottomed tray (4) that supported the thin layer of grains. The air was exhausted (12). The drying air temperature at the chamber inlet was measured using precision digital thermometer, accurate to \( \pm 0.5 \) °C. Temperature of surface grains in the chamber was measured using a precision infrared thermometer, accurate to 1%. In each experiment, a psychrometer was used to take several readings of dry bulb and wet bulb temperatures along each run, and the averages (variations were very small) employed to calculate the air absolute humidity \( (h_o) \).

2.4 Application: Rough Rice Kernel Drying Model

The formulation was used to model drying of a rough rice kernel can results were compared with those reported in the literature. Analysis if deep-bed grain drying is usually based on heat and mass transfer models of thin layers grain which only the average effects of on a relatively large number of kernels or seed is considered. The differential equations for heat transfer (Equ 1 & 2) to be used to predict the moisture and temperature distribution within the kernel which gives a kernel drying rate equivalent it the experimentally determined thin layer drying rate.

Figure 2. Schematic of thin-layer drying equipment used in this work

1-power regulation panel, 2-drying chamber, 3-air toward drying, 4-mesh-bottomed tray chamber, 5-electrical resistance heaters, 6- air towards the heater, 7-manometric pressure meter, 8-motor of fan, 9-centrifugal fan, 10-damper, 11-Wheel, 12-air exhaust

The rough rice kernel was modeled as both a linear model as shown in figure 1 and as a nonlinear model in figure 2. In the both cases, a two-dimensional axisymmetric finite element grid was used. Each grid consisted of 1600, 3-noded elements and 861 nodes.

3. Results and Discussion

Moisture diffusion equation, (1), and heat transfer equation, (2), simultaneous were solved and those equations were used to predict moisture distribution within the kernel during drying. The drying of rough rice kernel was simulated as a nonlinear model. In the both cases, a two-dimensional axisymmetric finite element grid was used. Each grid consisted of 1600, 3-noded elements and 861 nodes and time step, \( \Delta t \), was 1 s. Nodal temperature values were predicted during the initial stages of drying (0-150min). The experimental results were available only for this period on drying.
3.1 Verification of the Finite Element Model
For experiment, thin layer rough rice, ‘Sepidrod’ variety, was dried with drying air temperature 47°C and during drying air velocity, relative humidity, and initial moisture content for rough rice were 0.25 m/s, 26%, and 38.69% (d.b.) respectively. During drying, moisture was measured every minute. A computer code for predicting the moisture fields inside a quarter rough rice kernel was developed using Fortran-90 language. Comparison between the simulated and the measured average moisture contents is shown in figure 3. It can be seen that the simulated results agreed well with the measured values. Figure 2 shows, the simulated and measured variation of the average moisture with drying time under air temperature 47°C, that the simulated moisture contents before 13 minute, between 13 and 123 min and then were a little higher, lower and higher than the measured, respectively. The similar results were reported for wheat [5, 12]; peanut [2]; maize [14, 15] and rough rice [22, 23].

3.2 Moisture Distributions
It is important to know the temperature and moisture distributions of the kernel during, because a combination of moisture and temperature gradients would produce greater stress levels in grain. In order to examine the moisture and thermal stresses in details to need the temperature and moisture distributions of grain [8, 4].

Figure 3. Simulated and measured average moisture contents for a rough rice kernel at initial moisture content of 38.69% (d.b.), $T= 47 \, ^\circ C$ and RH=24%.

Figure 4. Curves of equal moisture inside the grain. Moisture distributions at selected drying times for a rough rice (1/4 kernel shown) at initial moisture content of 38.69% (d.b.), $T= 47 \, ^\circ C$ and RH=24%.

Figure 4 shows the moisture content distribution inside the kernel at four selected times: 10, 50, 100 and 150 min under air temperature 47°C. However, moisture content changes were much slower than temperature changes. Initial stage of drying, the surface moisture content quickly decreased but the center moisture content was constant and then the moisture content of surface kernel changed...
slowly and inside kernel the moisture content decreased. The moisture distribution for different drying times was reported within a single wheat kernel by Jia and Sun (2000), maize kernel by Neményi et al. (2000) and barley by Haghighi et al. (1990).

4 CONCLUSIONS

A simulation model rough rice kernel drying has been developed by finite element method and verified by thin layer drying. The predicted average moisture values agreed well with the experimental results. Finite element models were used to simulate the single kernel drying in term of moisture distributions inside rough rice kernels. The moisture content distribution inside the rough rice can be supplied by simulation of drying with finite element method. The output of nonlinear model was compared to experimental data by others. This comparison showed a no significant statistical difference. Therefore the model can follow the drying processes very well.

Acknowledgements

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References


[13] Jia C. Study of heat and mass transfer inside grain kernel and
temperature pattern in grain storage bin, PhD Thesis, Beijing Agricultural Engineering University, Beijing, China, 1995.


Notation

<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>C</td>
<td>Element mass capacitance matrix</td>
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<tr>
<td>c</td>
<td>Specific heat J/kg °K</td>
</tr>
<tr>
<td>D</td>
<td>Diffusion coefficient M²/s</td>
</tr>
<tr>
<td>F</td>
<td>Element mass force vector</td>
</tr>
<tr>
<td>h</td>
<td>Convection heat transfer W/m² °K coefficient</td>
</tr>
<tr>
<td>hₘ</td>
<td>Surface mass transfer coefficient m/s</td>
</tr>
<tr>
<td>K</td>
<td>Element mass conductance matrix</td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity W/m °K</td>
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<td>L</td>
<td>Latent heat of vaporization J/kg of water</td>
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<tr>
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<td>Number of element</td>
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<td>Drying time S</td>
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<tr>
<td>V</td>
<td>Volum</td>
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<tr>
<td>X</td>
<td>Moisture content d.b.</td>
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Greek symbols

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<tbody>
<tr>
<td>ρ</td>
<td>Density Kg/m³</td>
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Subscripts

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<tbody>
<tr>
<td>e</td>
<td>Equilibrium</td>
</tr>
<tr>
<td>∞</td>
<td>Ambient air</td>
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