Investigation of Simulation Heat Transfer within the rough Rice (Binam) Kernels during Drying

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Abstract
Diffusive kinetics models are used to interpret the phenomenon of drying of individual solids particles or thin layer drying. The main goal of this study is to give a mathematical model with numerical solution to follow the heat distributions inside a cross sectional area of an individual rough rice ‘Binam’ variety kernel as a 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 linear and nonlinear coupled conductive heat and diffusive moisture transfer equations 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 temperature 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.

1 Introduction
Artificial drying of biological products is one of preservation. Proper drying procedures can eliminate the potential of spoilage during subsequent storage and improve the quality of the grain. Rapid drying can increase brittleness and induce internal cracking which leads to the breakage during subsequent handling. Therefore, the drying process should be described accurately and controlled carefully so that techniques are available for designing the most appropriate dryer for reducing or eliminating drying damage to grain [1]. However, the thin-layer drying equations are still mainly used to calculate the grain average temperature and moisture content, and hence the process of heat and mass transfer within grain kernels cannot be modeled [19,20]. As the result, many complex-drying techniques such as tempering cannot be simulated [12].

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 [24, 25, 16]. 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 [7, 17, 9, 10, 11].

Grain kernel drying is a complex physio-thermal process. Considerable research has been conducted to numerically simulate the temperature and moisture fields within a grain kernel during its drying process. Most numerical simulation was based on grain drying models derived from a mechanistic approach or nonequilibrium thermodynamics [7,4]. Gustafson et al. did the finite element analysis of temperature distributions for a maize kernel during heating or cooling, the temperature distribution at various times within a maize kernel subjected to a step change in environmental temperature was predicted [5]. Haghighi and Segerlind and Haghighi et al. introduced the finite element method to simulate heat and mass transfer for grain drying, and the soya bean drying was taken as an example to predict the average temperature as a function of drying duration [7, 8]. Miketinac et al. used the finite element method to solve the non-linear coupled systems of two partial-differential equations describing the thin layer drying process of grain and calculated the heat and mass transfer coefficients using the inverse method [18]. Casada and Young developed a model to predict heat and moisture transfer for long-term moisture migration of peanuts due to natural convection and diffusion in arbitrarily shaped porous media [2]. Jia et al. performed simulation of temperature and moisture fields inside a maize kernel through finite element method [10, 12]. Yang et al. applied the finite element method to predict intra-kernel moisture content distribution during drying and tempering processes of rice and examined the relations between the moisture content gradients, head rice yield trends during drying and tempering processes and in 2003 they examine the relationship of intra-kernel moisture content gradients and glass transition temperatures to head rice yield trend for rough rice undergoing heated-air drying by finite lement method [22, 23]. Wu et al. developed mathematical model describing the simultaneous heat and mass transfer for the single kernel rice drying process [21] Haghighi and segerlind and Fortes et al. also reported that a combination of moisture and temperature gradients would produce greater stress levels in grain [7,4]. In order to examine the moisture and thermal stress in details, it is important to know the temperature and moisture distributions of the kernel during drying, particularly in the early stage of drying [4, 14] and this research was obtained temperature distribution within kernel during drying.

2 Materials and Methods

2.1 Mathematical Model of Heat and Mass Transfer

This study are used literary sources to set up a two-dimensional mathematical model are: Crank [3], Husain et al. [8], Gustafson et al. [5], Haghighi and Segerlind [7], Haghighi et al. [6], Lague and Jenkins [17] and Yang et al. [23]. The mathematical models applied by these authors were similar but the geometrical models were sometimes different. Every writer agreed that the temperature distribution within the geometrical model (spherical or cylindrical coordinate system, real geometrical model followed the real shape of a rough rice kernel in cylindrical coordinate system) was not uniform. Simultaneous equations for moisture and heat diffusion were needed to describe the heat flux within a rough rice kernel. For grain drying simulation, the fick’s diffusive equation describing the mass transfer process has been extensively applied, i.e [15].

\[
\frac{\partial M}{\partial t} = \text{div}(DM) 
\]  

Where M 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:

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

Where \( \rho \) is the density (kg/m\(^3\)); \( c \) 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:

\[
\begin{align*}
D \left( \frac{\partial M}{\partial t} \right) + h_m(M - M_\infty) &= 0 \\
k \left( \frac{\partial T}{\partial t} \right) + h(T_s - T_\infty) &= 0 \\
t = 0, M = M_0, T = T_0
\end{align*}
\]  
(3)

(4)

2.2 Finite Element Analysis

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

\[
T^{(i)}(r, z, t) = \sum_{j=1}^{n} N_j(r, z, t)T_j^{(i)}(t)
\]  
(6)

Where \( n \) is the total number of nodes in the element. Using the Galerkin weighted residual method and setting the integral of the residual function equal to zero yields:

\[
\int \int \int N_j \left( - \nabla^T K(r, z, t) \nabla T(r, z, t) + L \frac{\partial M(r, z, t)}{\partial t} + \rho c \frac{\partial T(r, z, t)}{\partial t} \right) \partial V = 0
\]  
(7)

Simplifying the results, an expression for the ith node in the element can be written as:

\[
\int \int \int N_j \left( - \left( \frac{\partial}{\partial r} \left( k \frac{\partial T^{(i)}(r, z, t)}{\partial r} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T^{(i)}(r, z, t)}{\partial z} \right) \right) + \frac{\partial M^{(i)}(r, z, t)}{\partial t} + \rho c \frac{\partial T^{(i)}(r, z, t)}{\partial t} \right) \partial V = 0
\]  
(8)

Where \( \dot{T} \) is the time derivative of \( T \) or \( k \frac{\partial T}{\partial t} \) and it is the temperature flux in the direction normal to the surface. For axisymmetric problems, \( \partial V = 2\pi rdz \), \( ds = 2\pi rd\theta \), and Eqn (8) becomes:

\[
2\pi \int N_j(r, z) \left( k \int \left( \frac{\partial N_j(r, z)}{\partial r} + \frac{\partial N_j(r, z)}{\partial z} \right) \frac{\partial T^{(i)}(r, z, t)}{\partial r} + \frac{\partial N_j(r, z)}{\partial z} \frac{\partial T^{(i)}(r, z, t)}{\partial z} \right) r dr dz
\]  
(9)

Eqn (9) can be written in a simplified form as:

\[
K_j T_j - C_m M_j + C_T \dot{T}_j = F_j
\]  
(10)

Where \( K \) is element thermal conductance matrix; \( C_m \) is element mass capacitance matrix; \( C_T \) is element thermal capacitance matrix; \( F \) is element thermal force vector; \( \dot{T} \) is the time derivative of \( M \) or \( \frac{\partial M}{\partial t} \) and coefficient of above equation is:
A simulation program using the finite element method, based on the above analyses, was developed by solving Eqn (21). Because of the initial nodal values of a single grain kernel such as temperature are given, for every time step (Δt), a set of new nodal values in the next time step can be calculated. By repeating this procedure, the temperature fields are obtained.

The base on Eqn (21) was programmed. The rough rice drying simulation program contains the components related to dimension of kernel, data input, drying–air conditions, grain initial conditions and computation, and data output (temperature of kernel surface and temperature during drying distributions). 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.

The accuracy of a mathematical model depends on the accuracy of the values of the thermo physical constants and variables. The heat convection coefficient is (47.65 W/m² °K). The latent heat of vaporization of water depends on the temperature and specific heat and conduction heat transfer coefficient depend on the moisture content of grain during drying. The cross-section dimensions and geometry of an individual rough rice kernel were introduced by Rafiee (2003). The average height of the cross-section of individual rough rice ‘Binam’ variety is 9.1 mm and the width of that is 2.4 mm. This cross-section is divided into three parts namely endosperm, bran and hull. The surface mass transfer coefficient is 0.571 (m/s).

2.3 Experimental Data Used

Registered seed grade medium rough rice ‘binam’ variety, grown in Kelardasht, Province Gillan, Iran, was used. The rice was harvested 2001/2002 season and was naturally dried in the field and received free from broken grains and foreign material. The material was divided into 3 (100 g) samples, which were moistened and were added necessary amount of water to obtain...
several initial moisture content values \( (M_o) \). Moistened samples were placed in airtight plastic containers and kept for at least 72 h in a cold store at 12°C to allow moisture to distribute inside the kernels while preventing any considerable microbial growth. The values for \( (M_o) \) obtained were 28.5% d.b. The containers were transferred from the cold store to the dryer chamber and immediately were dried. The samples dried by experimental thin layer dryer.

3. Results and Discussion

The differential equations for heat transfer (Eqn 1 & 2) to be used to predict temperature distribution within the kernel during drying. The rough rice kernel was modeled as both a linear and 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. To avoid numerical oscillation, a time step \( \Delta t \) of 1 s was chosen for the analysis. Nodal temperature values were predicted during the initial stages of drying (0-300s). The experimental results were available only for this period on drying.

The comparison of the simulated surface temperature of the kernel with the experimental data is shown in Fig 2. The linear model values are higher (average 3.70°C) and the nonlinear model values are lower (average 0.12°C) than the experimental ones during the whole drying process. Fig. 2 shows that the kernel surface temperature reaches the drying air temperature in about 140 sec. This rapid temperature rise in the kernel would therefore cause high thermal stress, which would damage the grain kernel during this period. Therefore, if high drying air temperature is used, the drying time should be controlled carefully because the maximum temperature gradient only occurs during the first few minutes of drying. Results presented here are consistent with those obtained by some researchers who studied this subject [13, 15].

![Figure 2. The comparison among linear and nonlinear models and experimental data. \( T_0 = 22^\circ C, T_a = 60^\circ C \) and RH=22%.](image)

The estimated temperature at two locations in the rice kernel (centre and surface) is illustrated in figure 3. The temperature of the kernel center did not increased significantly during the first 10 sec of drying. After that, it increased. The temperature of kernel surface was almost decreased during the first 5 sec of drying and then increased after that time. Higher temperature gradients cause higher thermal stress which contribute to initiation of cracks at the surface of kernel [6,7]. The kernel surface temperature may have been lower than the air temperature because of evaporation of moisture.

![Figure 3. Comparison of temperature variation in rough rice at the centre and surface during drying. \( T_0 = 22^\circ C, T_a = 60^\circ C, \) and RH=22%.](image)
Fig. 4 illustrates the intra–kernel temperature responses during a high–temperature (60°C) at kernel center into kernel surface, immediately following a drying process at the same temperature, at 1, 2, 5 and 10 seconds. As soon as drying began, the temperature at kernel surface decreased because moisture of kernel surface evaporated and heat for converting water to gas was obtained of grain. Temperature difference between center and surface gradually decreased. Therefore with time the heat gradient decreased [4,7]. The temperature difference between the surface and the interior of kernel, after 1s, 2s, 5s and 10s of drying, were calculated and the temperature distributions within the kernel are -6.4, -1.8, 1.7 and 2.9°C, respectively. After 1s of drying (Fig 4), the temperature difference between the surface and the interior of kernel is very greater than 2s of drying.

4. Conclusions

The details solution of the non-linear partial differential equations for heat transfer using finite element method was presented and a computer program was developed and simulated the temperature field within a single kernel with three different layers (Endosperm, bran, and hull). The simulation Data are examined using values that were obtained thin layer drying experiments on ‘Binam’ variety rough rice kernel, and the comparison shows that the simulation program gives good prediction in temperature distribution.

The temperature distribution inside the rough rice kernel during drying can be simulated by finite element method. In initial stage of drying, the large amount of moisture is evaporated of surface of the rough rice kernel thus surface of the kernel thermal decrease very quickly and then it is increase. Therefore, the temperature distribution inside the kernel is very uneven in the early stage of drying [4, 14]. As the drying process continues, the temperature distribution becomes even very rapidly. However, the effect of temperature gradients only existed in the very initial stage of drying (about 2 to 120 s) [23].

Acknowledgements

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**Notation**

- A: surface area of a grain kernel, $m^2$
- C: Element capacitance matrix
- c: Specific heat, $J/kg\ °K$
- D: Diffusion coefficient, $m^2/s$
- F: Element thermal force vector
- h: Convection heat transfer coefficient, $W/m^2\ °K$
- $h_m$: Surface mass transfer coefficient, $m/s$
- K: Element thermal conductance matrix
- $k$: Thermal conductivity, $W/m\ °K$
- L: Latent heat of vaporization of water, $J/kg$
- M: Moisture content, d.b.
- m: Number of element
- n: Number of node
- T: Temperature, $°K$
- t: Drying time, S
- V: air velocity at kernel surface, $(m/s)$
- $\rho$: Density, $kg/m^3$
- $\Theta$: Relaxation parameter
- 0: Initial
- A: Drying air
- e: Number of element
- m: Related to moisture
- S: Surface of kernel
- T: Related to temperature
- $\infty$: Ambient air