Numerical Analysis of Heat and Moisture Transfers in a Rice Grain

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Abstract

Governing equations describing the simultaneous heat and mass transfers for a rice grain during a drying process were solved by using a CFD code based upon the finite volume method. The rice grain was modeled as a continuous ellipsoid divided into three layers: hull, bran and endosperm. Unsteady heat conduction and moisture diffusion took place within the kernel and convective heat and mass transfer took place between the kernel surface and the drying air medium. The initial and boundary conditions were given by initial temperature and moisture distributions inside the rice kernel, temperature and relative humidity of the heated air. The experimental results of a thin-layer drying test were used to validate the CFD prediction. It was found that the temperature gradient within the grain existed only in the first few minutes of the drying process. The moisture content gradient, however, was the major feature that affected drying features of the rice grain.

Keywords: CFD in paddy drying, Paddy drying, Grain drying

1. Introduction

Rice (sometimes called paddy) is an important agricultural product for world’s population especially in Asia. Most of rice is harvested at high moisture content; therefore rough rice is typically dried immediately after harvest for it to be stored safely. Drying is a costly but important step in rice production. Proper drying helps improve rice grain quality and increase storage time. Improper drying process, however, can reduce head rice yield and milled rice quality. An ideal drying process produces dried rice grains at a highest rate, highest quality and lowest cost.

Drying of rough rice is a very complicated process. A theoretical drying model needs proper governing equations along with boundary conditions. Moisture and heat transfers inside and outside a rough rice kernel are two governing physical processes that occur simultaneously and interactively since evaporation of liquid into vapor consumes latent heat. Due to its importance and complexity paddy drying has been an area of intensive research. Luikov [1] postulated a set of governing equations for rice drying which coupled the two transfer processes. Most researchers have applied these equations to predict grain drying. Husain et al. [2] presented a model of simultaneous heat and mass transfer based on Luikov’s equations; the predicted results on rough rice drying agreed well with the experimental data. Numerical study was performed by Sarker et al. [3, 4] who used finite element method to compute rough rice drying rate. The studies indicated that the transient moisture gradient is highest along the long axis and located near the middle of the grain. Jia et al. [5] developed a mathematical model and afterwards Jia et al. [6] developed a computer simulation software using finite element method with graphical user interface that can be used to simulate single-kernel drying and subsequent tempering processes as well as internal stress distribution. Ranjan et al. [7] developed a three-dimensional (3-D) control volume model for temperature and moisture predictions on a rang of food materials. The overall predictions agreed well with the available experimental data and showed good potential for the application in grain and food drying. Wu et al. [8] used 2D and 3D finite volume methods to compute heat and mass transfer inside a single rice kernel. They found that it is sufficient to use the 2D simulation in determining important features inside a rice kernel such as the time for the occurring of maximum moisture content gradient.

The majority of the mentioned studies above assumed constant convective heat and mass transfer coefficients which is not quite an accurate representation of nature. Kaya et al. [9] studied spatial variation of convective heat and mass transfer coefficients of a rectangular moist object in an external flow using a CFD technique. They analyzed the external flow and the temperature field around the object to predict the variations of the convective heat transfer coefficients and used the boundary layer analogy to compute the mass transfer coefficients. The distributions of these coefficients were related to the boundary conditions and used to solve the heat and moisture transfers inside an object. The results showed good agreement with the experimental data taken from the literature.

So far computational drying technology is mainly a semi-theoretical procedure where boundary data such as heat and mass transfer coefficients are “specified” from experimental correlations. It is highly desirable that all
the transfer coefficients be “computed” rather than “specified”.

The ultimate objective of this study was to investigate the drying process of a rough rice grain by numerical simulation where all the transfer coefficients would be computed simultaneously with the external flow field and the internal diffusive field of the grain. At this stage of the study, however, complicated, external airflow is excluded and transfer coefficients at boundaries are specified.

2. Method

2.1 Theoretical considerations for drying

The modified form of the Luikov’s set of equations mentioned above was used in this study. The assumptions used together with the mathematical models are as follows: (1) the rice kernel is a continuous ellipsoid divided into three layers: hull, bran and endosperm (Fig. 1 and 2). (2) The heat conduction and moisture diffusion processes are unsteady and (3) heat and mass transfer coefficients are specified at grain boundary. (4) Shrinkage or deformation of the rice kernel during drying is negligible. (5) No heat generation inside the rice kernel, and (6) no effects of radiation. From the above assumptions, the governing equations describing the conservation of heat inside a grain has the following form:

\[ \frac{\partial}{\partial t} \left( \rho S_c T \right) = \nabla \cdot \left( \lambda \nabla T \right) \]  

(1)

where \( T \) is temperature [°C], \( t \) is time [sec], \( \rho S \) is kernel density [kg-m\(^{-3}\)], \( c_s \) is specific heat capacity [J/kg·°C], and \( \lambda \) is thermal conductivity [W·m\(^{-1}\)·°C\(^{-1}\)].

Likewise, the Fick’s diffusive equation [1] or the moisture transport equation can be written as:

\[ \frac{\partial}{\partial t} \left( \rho_b \Phi \right) = \nabla \cdot \left( \rho_b D_b \nabla \Phi \right) \]  

(2)

where \( \Phi \) is moisture content [dry basis, d.b. (defined as the water per dry mass of the solid body)], and \( D_b \) is diffusion coefficient [m\(^2\)·s\(^{-1}\)].

2.2 Boundary and initial conditions

For the conservation of heat equation, the boundary condition is,

\[ -\frac{\lambda}{\partial n} T = h_i(T - T_0) \]  

(3)

where \( n \) is the normal direction to the rice surface, \( h_i \) is convective heat transfer coefficient [W·m\(^{-2}\)·°C\(^{-1}\)], and \( T_0 \) is ambient temperature. For the conservation of mass equation, the boundary condition is,

\[ -D_b \frac{\partial \Phi}{\partial n} = h_m(\Phi - \Phi_e) \]  

(4)

where \( \Phi_e \) is equilibrium moisture content of the grain in the surrounding air and \( h_m \) is convective mass transfer coefficient [m·s\(^{-1}\)]. The initial conditions for both equations are:

\[ \Phi = \Phi_{0i}, \ T = T_0 \]  

(5)

where \( \Phi_{0i} \) is initial moisture content of the kernel and \( T_0 \) is initial temperature of the kernel.

Correlations for \( h_i, h_m, \lambda, \rho_b, c_s, D_b \) and \( \Phi_e \) are now presented. Lage and Jenkins [10] used the following equations to determine \( h_i, h_m, \lambda, \rho_b \) and \( c_s \):

\[ h_i = 16.09 + 65.87 \times u^{0.53} \]  

(6)

\[ h_m = 0.01959 + 0.08073 \times u^{0.53} \]  

(7)

where \( u \) is mean velocity of the air [m·s\(^{-1}\)].

\[ \lambda = \left( \frac{0.0637 + 0.0958 \times \Phi_{ave}}{0.656 - 0.475 \times \Phi_{ave}} \right) \]  

(8)

where \( \Phi_{ave} \) is average moisture content of the rice kernel in kg-water/kg-dry-grain and \( \Phi_{ave}^* \) is average moisture content in kg-water/kg-wet-grain, wet basis [w.b.].

\[ \rho_b = A_i \times \frac{1456 + 705 \times \Phi_{ave}^*}{1 + \Phi_{ave}^*} \]  

(9)

where \( A_i \) are constants for endosperm, bran, and hull layers equaling to 1.257, 1.493, and 0.532, respectively. The specific heat models were adopted from Lage and Jenkins [10], as follows:

\[ c_{endosperm} = 1180 + 3766 \times \Phi_{ave}^* \]  

(10)

\[ c_{bran} = \frac{1}{1201 + 3807 \times \Phi_{ave}^*} - 0.875 \]  

(11)

\[ c_{hull} = \frac{0.2}{1109 + 4677 \times \Phi_{ave}^*} - 0.1 \]  

(12)

The kernel moisture diffusivities were calculated using the formulas from Lu and Siebenmorgen [11]:

\[ D_{endosperm} = \frac{1.6163}{3600} \times \exp \left[ \frac{-5289.5}{T_{ave} + 273.15} \right] \]  

(13)

\[ D_{bran} = \frac{110.969}{3600} \times \exp \left[ \frac{-7042.5}{T_{ave} + 273.15} \right] \]  

(14)

\[ D_{hull} = \frac{3.0101}{3600} \times \exp \left[ \frac{-6000.5}{T_{ave} + 273.15} \right] \]  

(15)

where \( T_{ave} \) is average temperature of the rice kernel. For the equilibrium moisture content of the drying air, the value in ASAE Standards [12] was used:

\[ \Phi_e = 0.29394 - 0.046015 \ln[-(T_0 + 35.703) \ln(RH)] \]  

(16)

where \( RH \) is relative humidity of drying air in decimal.

2.3 Experimental Data

Experimental data on thin layer drying of rice conducted by Cnossen and Siebenmorgen [13] and Yang et al. [14] were used to verify the present simulation. The conditions used in the experiment are as shown in Table 1. The initial temperature of the rice kernels in all cases was set at 29°C and the velocity of the air blown to the thin layer of rice was set as 0.11 m·s\(^{-1}\).

<table>
<thead>
<tr>
<th>Case</th>
<th>( T_0 ) (°C)</th>
<th>%RH</th>
<th>( M_{0i} ) [%w.b.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>60</td>
<td>17</td>
<td>21.1</td>
</tr>
<tr>
<td>II.</td>
<td>42</td>
<td>30</td>
<td>16.4</td>
</tr>
<tr>
<td>III.</td>
<td>38</td>
<td>47</td>
<td>21.3</td>
</tr>
</tbody>
</table>
2.4 Dimensions

In this study, it is assumed that the rice kernel is an ellipsoid as shown in Fig. 1.

![Figure 1. The volume of the ellipsoid with semi-axes a b c](image)

Long-grain Cypress rice was used in this study. The ellipsoid assumes the following dimensions: 8.83 mm in the longitudinal axis, 2.48 mm in the short axis and 1.92 mm in the shortest axis [8]. Figure 2 depicts these dimensions together with the three-layer structure.

![Figure 2. Dimensions of the hull, bran and endosperm within a single rice kernel (1/4 section).](image)

2.5 Simulations

The Computational Fluid Dynamics code [15] was chosen to carry out the simulation of the drying process. For this purpose, the CFD code solves the conservation and the transport equations by using finite volume method. The computational grid was generated using unstructured tetrahedral mesh methodology. The single rice kernel was modeled as axis-symmetry where the centerline along the longitudinal axis is the axis of symmetry. The axis-symmetric characteristic of the problem was simulated by a 2D computational domain with a wedge of 15º formed in the third direction (see Fig. 3). Due to symmetry, only a quarter of the entire cross section was computed. The domain was discretized into 4,881 triangular elements with a total of 1,487 nodes. The CFD code solves two transport equations for two unknowns: temperature and moisture content. Time-dependent simulations were performed with time step size equaling to (i) 1 sec. for the early stage of drying; (ii) 1 min. afterward; this is to be consistent with the rates of drying in those drying intervals.

![Figure 3. Unstructured grid using for 15 degree wedge, axisymmetric computational domain.](image)

Proper initial and boundary conditions are needed for a successful computational work. The initial conditions specified were the values of the temperature and moisture concentration of the grain and the surrounding air. Afterward, temperature and moisture boundary conditions, as indicated in Eq. (3) and (4), were employed at the outer surface of the grain. The ‘symmetry’ boundary conditions were applied at the high-θ and low-θ planes, and at the cross sectional face of the wedge. All the test cases were computed until residuals of all equations converges. Moreover, convergence of the simulation was reassured by monitoring the mass conservation of the flow field.

3. Results and Discussion

The comparison of the temperature at the center of the kernel with the experimental data of Yang et al. [14] is shown in Fig. 4. In the original computation (Simulation 1) the differences between the two results are quite large, especially at the early stage of drying. The disagreement was believed to result from the inappropriate values of the various parameters that were not measured specifically for the Cypress rice used in the experiment. The formulas for the properties of rice were obtained from the literatures; for example the mass diffusion coefficient was developed for the rice variety ‘Newbonnet’. There are a few parameters related to the heat transfer rate, namely, the specific heat of rice $c_{p}$, the thermal conductivity $\lambda$, and the convective heat transfer coefficient $h$. A correction was made to $c_{p}$ by multiplying a correction factor obtained by trial and error. In Fig. 4, ‘Simulation 1’, ‘Simulation 2’ and ‘Simulation 3’ represents the simulated result where $c_{p}$ was multiplied by 1.0, 0.8 and 0.6, respectively. It can be seen that the results of ‘Simulation 3’ agree best with the experimental data. Other parameters had also been varied but did not contribute to significant changes of the temperature profile. Note that the temperature of the kernel center reached the drying air temperature within about 2 minutes. This rapid temperature rise results in high thermal stress which could damage the grain kernel [4].

![Figure 4. Measured and simulated center temperature of a rough rice kernel at 60°C drying air and 17% RH.](image)
Numerical calculations were executed for the three drying cases as indicated in table 1. As in the case of temperature, preliminary results showed a large difference in average moisture contents. Convective mass transfer coefficient $h_m$ and mass diffusion coefficient $D_Φ$ are major parameters that are related to mass transfer rates. To this end, a correction was made to $D_Φ$ by multiplying it with a correction factor in a whole grain while keeping the convective mass transfer coefficient unchanged. Comparisons of the average moisture contents of a whole kernel for the three cases are shown in Figs. 5−7. ‘Simulation 1’ and ‘Simulation 2’ represent the simulated result without and with a correction to $D_Φ$, respectively. Case I in Fig. 5 was not corrected; cases II in Fig. 6 was corrected by 1.2 and case III in Fig. 7 corrected by 1.8. It can be seen that the correction factors help improve the predictions to be comparable with the experimental data. The correction factor for the mass diffusion coefficient, $c_D$, could be related to the drying air temperature in a quadratic form as:

$$c_D = 17.1727 - 0.6348T_a + 0.006056T_a^2$$ (19)

The gradients of moisture have been identified as the major source in fissuring of a rice grain. Sharp decreases in moisture contents could be observed during the first few minutes of drying period; afterward the moistures decrease much slower. This behavior is well known in rice drying and it was predicted very faithfully by the computation.

Various researchers have reported that a combination of moisture and temperature gradients produce greater stress levels in grain. Because the temperature gradient only exists in the first few minutes of drying process; thus it should have less effect on fissuring than the moisture content gradients; therefore, most researchers [3,7,14] omitted reporting temperature profiles. On the contrary, the contribution of moisture content gradients is comparatively small in the early stage of drying when the moisture removal from the kernel is limited, but becomes more pronounced as drying proceeds [16].

In order to examine the moisture and thermal gradients in detail, it is important to know the temperature and moisture distributions in the kernel. One advantage of CFD is that temperature and moisture fields over the whole computation domain at each time step are available. The temperature distribution within the kernel after 30 sec. of case I is shown in Fig. 8. It shows that in the initial stage of drying, there exists a big temperature difference between the surface and the interior of the rice kernel (the temperature difference is about 5ºC after 30 sec.) As the drying process continues, the temperature distribution levels off rapidly. Therefore, the drying process needs to be managed carefully in order to minimize the damage that may arise form the thermal stress within the kernel.

Calculation of maximum temperature gradients were also carried out in this study. Here, temperature gradient is defined the temperature difference between the outer
bran node and the center node of the grain kernel divided by the distance between them. The temperature gradient along the two axes (long and short axes) is shown in Fig. 9. It is seen that the maximum temperature gradient appeared within 5-10 sec. after the onset of drying and the temperature gradients leveled off after 2 min., this agrees with the findings reported by Yang et al. [14]. It can also be seen that the maximum temperature gradient along the short axis is nearly double that of along the long axis. Because the maximum temperature gradient only occurs during the first few minutes of drying, therefore if high drying air temperature is used, the drying process should be managed carefully in order to lower the gradient.

Contrary to the temperature distribution, the moisture distribution within the kernel drops slowly as in portrayed in Figs. 10-11. The computed moisture contents at three selected nodes in the rice kernel under drying condition of case I is illustrated in Figure 11. Since the drying process took place from the outer shell to the interior of the kernel, the moisture contents of the center node were almost unchanged during the first 20 min. before it decreased slowly afterward. The moisture contents at the shell of the short axis node decreased more quickly than at the long axis node.

The moisture gradient is the driving force for moisture diffusion from the inner layers to the surface. The rice grain is hygroscopic and presents dynamic physical response to moisture and temperature changes in the surrounding air. A wet grain surface desorbs moisture in a relatively dry air. This occurs when the vapor pressure at the surface of a grain is higher than vapor pressure in the surrounding air. The moisture gradient within the kernel continues to increase cause an increase in drying rate. Sarker et al. [4] and Yang et al. [14] found that moisture content gradients inside the rice kernel had great effects on rice grain quality. The moisture content gradient is defined as the moisture content difference between the outer bran node and the center node of the grain kernel divided by the distance between them. Figure 12 shows the moisture content gradient along the two axes under the drying condition of case I, the maximum value was reached at 45 min. along the short axis. It is confirmed that the maximum moisture content gradient exists along the short axis, as reported by Sarker et al. [4]. A steep increase in moisture content gradient appeared in the early stage, followed by a gradual decline. Therefore, proper techniques such as tempering and intermittent drying should be adopted in order to ease the problem of fissuring and therefore improve milled grain quality after drying.
4. Conclusion

The coupled heat and mass transfers inside a single rice kernel during drying were simulated by using CFD to solve temperature and moisture content equations. Theoretical predictions of local temperature and average moisture content of rice kernels were verified by experiment data. The predicted temperature and moisture distributions agree well with the measured data. The maximum moisture content gradient and maximum temperature gradient are found to occur along the short axis of a rice kernel. The effect of temperature gradients only exist in the initial stage of drying (about 2 min.) The maximum moisture content gradient occurs much later than the maximum temperature gradient, at about 45 min. CFD simulation, if used properly, could be used quite accurately to analyze and improve efficiency and quality in grain drying.

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References

12. ASAE., 2001. ASAE Standards. D245.5: Moisture Relationships of Plant-Based Agricultural Products. ASAE, St. Joseph, MI.