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Effect of Geometry of Rice Kernels on Drying Modeling Results

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Geometry of rice grain is commonly represented by sphere, spheroid, or ellipsoid shapes in the drying models. Models using simpler shapes are easy to solve mathematically; however, deviation from the true grain shape might lead to large errors in predictions of drying characteristics such as moisture content (MC) and moisture gradients (MG). This research was undertaken to determine the impact of such shape considerations on prediction of drying characteristics. Impact of shrinkage of grains caused by drying was also investigated. Three separate mathematical models, each representing rice grain by sphere, spheroid, and ellipsoid shapes, were developed to describe the drying process. These models were solved by the finite element method using Comsol Multiphysics® simulation program. Drying simulations showed important differences in predictions of MC and MG in these three models. The sphere-shaped model predicted a slower drying than the spheroid- and ellipsoid-shaped models, whose MC predictions were similar. In all three models, maximum moisture gradients (MMG) were observed along the shortest axis in the bran region. During drying, MMG increases, reaches a peak, and then decreases. Magnitude and onset of peak of MMG were different in the three models. These differences in drying predictions among the three models make it important to use the appropriate shape to represent the rice grain in mathematical models. Ellipsoid shape, which closely resembles geometry of the rice grain, was found to be the most suitable. Reliable MG predictions from such ellipsoid-shaped models could be correlated to grain fissuring, which thereafter can be employed to optimize the drying process. The impact of shrinkage of rice grains during drying on model predictions is very small. In any drying simulation, maximum error due to neglecting shrinkage would be less than 5% of total moisture loss value.

Keywords Grain shape; Mathematical modeling; Rice; Shrinkage

INTRODUCTION

Mathematical modeling of moisture movement within a rice kernel during drying was researched comprehensively in the last five decades.[1–9] The main objective of these studies was to predict moisture content (MC) of the rice grain after a certain drying period. These mechanistic models assisted in understanding the impact of factors affecting the drying process, such as drying air temperature and speed of drying air. Some models[4,5] also specifically predicted moisture gradients (MG) within the rice kernels, which are believed to cause the kernels to fissure and thus reduce economic value of the crop. Prediction of MG also assisted in determining the duration of tempering in multi-pass heated air drying.[5]

Developing mathematical models for irregularly shaped rice kernels is complex and hence, in most modeling studies, rice kernels were approximated to simpler shapes such as sphere, spheroid, or ellipsoid. Depending on the selection of the shape, models were solved in one (sphere), two (spheroid), or three (ellipsoid) dimensions by numerical methods such as finite difference method or finite element method. Although most reported models were able to predict MC successfully, inaccurate geometric representation of the rice kernel might result in a misleading prediction of MG values. In this study, we have investigated the impact of different shape considerations in rice drying models on predictions of MC and MG. To accomplish this, three models, each representing rice grains by sphere, spheroid, and ellipsoid shape, were developed. These models were then solved in the same drying conditions and their prediction of MC and MG were compared.

Most drying modeling studies neglect shrinkage of rice grains during drying and assume size of rice grain to be the same. In reality, sizes of grains depend on MC[10,11] and change during the drying process. Impact of such changes in size on drying curves was also determined.

Based upon length-width ratio of milled rice, the rice varieties are normally classified into three grain types: long, medium, and short. Length-width ratio for long grain rice is larger than 3.0, medium grain rice is 2.0 to

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2.9, and short grain rice is lower than 2.0.[12] Due to the differences in shape and size, rough rice of these three types of rice varieties are expected to dry differently. Such differences in drying curves were also investigated in this study.

Objectives of this study are:

1. To develop three separate mathematical models to describe drying in rough rice kernels represented by sphere, spheroid, and ellipsoid shapes.
2. To compare predictions of moisture content (MC) and moisture gradients (MG) in the rice kernel in these three drying models.
3. To determine impact of shrinkage on drying curves of rice grain.
4. To compare drying curves of rice kernels of long, medium, and short grain varieties.

MODEL DEVELOPMENT

Three different shapes (sphere, spheroid, and ellipsoid) were selected to represent the rice kernel in three separate mathematical models. In each model, the rough rice kernel was assumed to contain three isotropic components, namely endosperm, bran, and husk (Figure 1). The size of each component was estimated by measuring length (a, m), width (b, m), and thickness (c, m) of white rice, brown rice, and rough rice kernels of Californian M206 rice variety (Table 1). Volume (V, m^3) of rice kernels was estimated using the following formula:[13]

$$V = \frac{4}{3}\pi abc \tag{1}$$

In the case of sphere- and spheroid-shaped models, equivalent radii were determined by equating the volume of sphere and spheroid to the volume of the kernel.[14] For the sphere-shaped model, radius (R_1, m) was calculated as:

$$R_1 = \left(\frac{3}{4\pi}V\right)^{1/3} \tag{2}$$

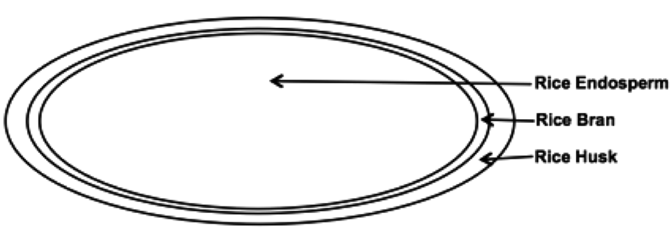

FIG. 1. Three components of rough rice grain in the drying models.

TABLE 1
Kernel dimensions of different forms of rice variety, Californian M206, at 18% MC on dry basis

Rice form	Length (mm)	Width (mm)	Thickness (mm)
White Rice	5.78 ± 0.23	2.66 ± 0.11	1.85 ± 0.08
Brown Rice	5.82 ± 0.33	2.78 ± 0.09	1.97 ± 0.08
Rough Rice	6.97 ± 0.32	3.16 ± 0.19	2.19 ± 0.09

For the spheroid-shaped model, length (L, m) and radius (R_2, m) were determined as:

$$\begin{aligned} L &= a \\ R_2 &= \sqrt{bc} \end{aligned} \tag{3}$$

Different theories were proposed to explain the mechanism of internal moisture movement during falling-rate drying in biological materials.[15,16] Some of them are: difference in vapor pressure, liquid diffusion, capillary flow, pore flow, unimolecular layer movement, multimolecular layer movement, concentration gradient, and solubility of the absorbate. Each of these theories explains some aspects of drying in some materials but no universally applicable theory has been substantiated by experiments.[15] Despite the uncertainty about the actual mechanism of moisture movement, most researchers[1–9] have described moisture movement in rice drying by Fick's laws of diffusion. These models predicted average moisture of the grain reasonably well. However, it should be noted that this alone does not establish diffusion as the mechanism of moisture movement in rice. A true criterion for the validity of the mechanism would be accurate prediction of moisture distribution within the grain,[17] which has not yet been fully considered in rice drying.[18] Unless measurement methods are developed to determine moisture distribution within the rice kernel, the uncertainty about the actual mechanism would remain unresolved.

In this study, liquid diffusion was considered as the mechanism of moisture movement within the kernel. The embryo (germ) region, which is roughly 1–3% of the total grain by weight,[19] was not considered as separate component in the rice kernel. Shrinkage in size of the rice kernel during the drying simulation was neglected; however, its effect on drying was illustrated by using different size rice kernels. Evaporation of moisture was assumed to occur only at the kernel surface. These assumptions were frequently used in rice drying modeling studies.[2–5]

In all three drying models, Fick's second law of diffusion in a three-dimensional Cartesian coordinate system was used to model the moisture transport process within the rice kernels during the drying processes. It should be noted that, using symmetry about axes, sphere-shaped and spheroid-shaped models can be solved in one and two dimensions, respectively. However, for the sake of ease in comparison, all three models were solved as three-dimensional objects. The governing moisture transport equation with initial and boundary conditions is given by:

Governing moisture transport equation:

$$\frac{\partial M(x,y,z,t)}{\partial t} = D\nabla^2 M(x,y,z,t) \tag{4}$$

Initial conditions:

$$M(x,y,z,0) = M_i \tag{5}$$

Boundary conditions:

$$-D\nabla M(x,y,z,t) = h_m(M(x,y,z,t) - M_e) \tag{6}$$

where t is time (s), ∇ is divergence operator, D is effective moisture diffusivity (m^2/s), M is the moisture content (kg water/kg dry solids), M_i is the initial moisture content (kg water/kg dry solids), M_e is the equilibrium moisture content of rice corresponding to drying conditions (kg water/kg dry solids), and h_m is the surface mass transfer coefficient (m/s).

At internal boundaries, i.e., endosperm-bran interface and bran-husk interface, continuity of moisture fluxes were considered. All three models were solved using Comsol Multiphysics® simulation program (Comsol Inc, Palo Alto), which uses the finite element method to solve the model equations. The representative meshed model geometry of rough rice in the three models is shown in Figure 2. Due to the existence of symmetry about the three axes in the rice kernel, one-eighth of the actual rough rice volume was sufficient to solve these models. The number of elements in rough rice models of sphere, spheroid, and ellipsoid shapes were approximately 10000, 6000, and 8000, respectively. These numbers of elements were considered sufficient because increasing their number did not lead to any higher accuracy.

Knowledge of effective moisture diffusivity, equilibrium moisture contents, and surface mass transfer coefficient are required to solve these mathematical models. Effective moisture diffusivity values of different components of rice kernels were determined by the procedure used by Steffe and Singh[2] and Lu and Siebenmorgen[20] and are described in detail by Prakash et al.[21] Based on drying experiments performed on Californian M206 rice variety, effective moisture diffusivity values of endosperm, bran, and husk at 45°C were determined and were 3.9×10^{-11}, 6.5×10^{-12}, $8.5 \times 10^{-12}\, m^2/s$, respectively.[22] Equilibrium moisture contents (EMC) of different forms of rice were experimentally measured. Surface mass transfer coefficient, h_m (m/s), was determined using the following relationship:[3,23]

$$Sh = \frac{h_m d_k}{D_{wa}} = 2 + 0.522\mathrm{Re}^{0.5} Sc^{0.33} \tag{7}$$

where Sh is the dimensionless Sherwood number, D_{wa} is diffusivity of water in air (m^2/s), d_k is equivalent diameter of the kernel (m), Re and Sc are dimensionless Reynolds number and Schmidt number, respectively. A dimensionless moisture ratio (MR, %), was used to compare drying curves of rough rice in different drying models and was defined as:

$$MR = 100 \times \frac{M_i - M_{av}}{M_i - M_e} \tag{8}$$

where M_{av} (kg water/kg dry solids) was average moisture content of the rice kernel at any given time. Moisture gradient (MG) at any point within the rice kernel model was determined in the simulation program using the following expression:

$$MG = |\nabla M| = \left[\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2\right]^{1/2} \tag{9}$$

where x (m), y (m), and z (m) are the three coordinates.

RESULTS AND DISCUSSION

Drying Curves Prediction

Each of the three models was solved to predict MC at a regular time interval during heated air drying of rough rice at 45°C. The drying curves obtained from these simulation results are shown in Figure 3. For the same drying periods, the ellipsoid-shaped model predicted the largest MR, i.e., the fastest drying, and the sphere-shaped model predicted the slowest drying. Such differences in drying curves could be due to differences in surface areas exposed to drying air in the three models. For the same volume, the sphere has the smallest surface area while the ellipsoid has the largest surface area, resulting in the aforementioned drying characteristics.

Differences between drying curves of the ellipsoid-shaped model and spheroid-shaped model were very small. After 20 min of drying, the difference in MR was less than

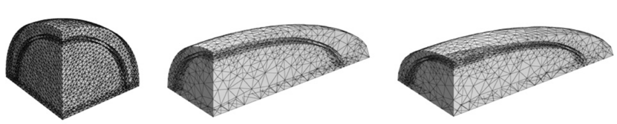

FIG. 2. Meshed geometry in drying models in shapes of sphere, spheroid, and ellipsoid (1/8 volume) in Comsol Multiphysics® simulation program.

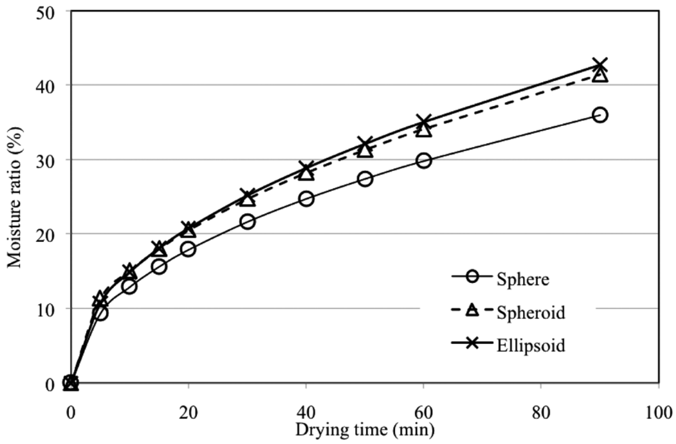

FIG. 3. Drying curves during heated air drying at 45°C in models of the three shapes.

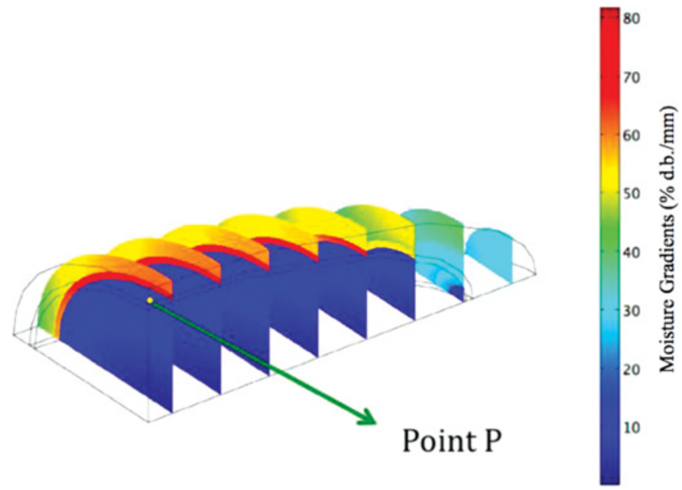

FIG. 4. Moisture gradient in the ellipsoid-shaped rough rice grain model after 20 min of heated air drying at 45°C (color figure available online).

1%. Therefore, if the key objective of research is to predict only MC after certain drying periods, the spheroid-shaped model could be used as effectively as the ellipsoid-shaped models.

Moisture Gradients Prediction

Simulations were run in the three models to determine moisture gradients (MG) within the rice kernel during drying. In these simulations, drying temperatures were 45°C and initial MC of rice 30% (on d.b.). In all three models, the highest moisture gradients were observed along the shortest axis in the bran region. This is because bran has the smallest moisture diffusivity among the rice components, which slows the movement of moisture across it. The presence of such high moisture gradients along the shortest axis, near the center of the kernel, might explain the occurrence of most fissures along the axial direction of the kernel.

Moisture gradients produced within the rough rice kernel after 20 min of drying in the ellipsoid-shaped model are shown in Figure 4. One specific point P, located inside the bran layer along the shortest axis, was selected as representative of the sites having maximum moisture gradients (MMG) inside the kernel in each model. Predicted MMG in the three models during drying simulations are shown in Figure 5. During drying, MMG first increases rapidly, reaches a peak, and then decreases at a much slower pace. Sarker et al.[4] and Yang et al.[5] reported such trends in MMG in spheroid-shaped models.

Lowering of MG after onset of peak should not be interpreted as reduced susceptibility of the rice kernel to fissuring. It is because fissures in the kernel are affected by both mechanical stresses and mechanical strength of the kernel. Fissures are caused when the mechanical stresses (caused by moisture gradients) exceed the kernel strength. Low moisture rice kernels have lower mechanical strength, which makes them susceptible to fissuring even at smaller magnitudes of moisture gradients.[24]

The three models predicted the magnitude and onset of peak of MMG differently. Magnitude of MMG peak was the largest in ellipsoid-shaped models, while it was the smallest in sphere-shaped models. Peak of MMG was reached earliest in the ellipsoid-shaped model and the latest in the sphere-shaped model. These MMG results are difficult to validate due to lack of experimental methods to measure the MG within the rice grain. Onset of the MMG peak could have consequences on fissuring in dried rice. Yang et al.[5] observed that continuing drying after reaching the peak led to more fissuring in rice.

In most commercial rice drying facilities, each active drying pass consists of about 20 min of heating followed by 4 to 24 hours of tempering. This duration of drying pass

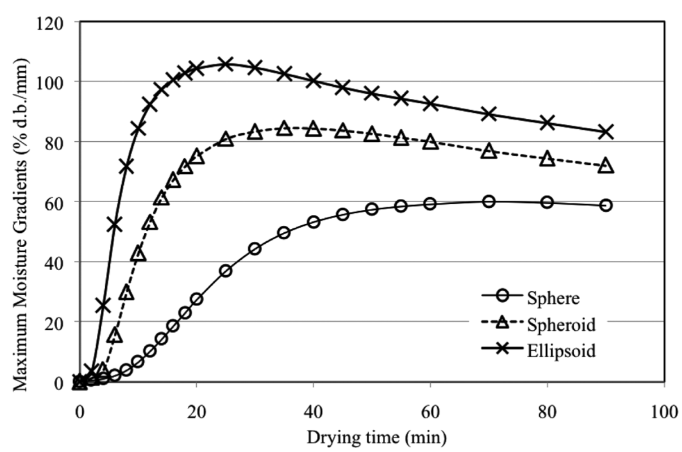

FIG. 5. Maximum moisture gradients (MMG) during heated air drying at 45°C in models of the three shapes.

was selected after performing experimental trials to minimize fissuring. Such foresight is clearly vindicated by MMG simulation results from the ellipsoid-shaped model, which predicts onset of peak at about 25 min. On the other hand, onset of peak for spheroid- and sphere-shaped models was 45 and 80 min. Considering the large differences in MG predictions among the three models, it seems critical to use the closest resembling shape (i.e., ellipsoid in this study) to represent the rice kernel for reliable application in rice fissuring research. Therefore, the ellipsoid-shaped model was selected to describe drying characteristics in the following sections of this study.

The ellipsoid-shaped model was used to predict MMG within the rice kernel during the heating and tempering stages of multipass drying (Figure 6). For this simulation, the heating pass consisted of 20 min while the tempering consisted of 4 hours and was performed at the drying temperature of 45°C. In this multipass drying, MG increased rapidly during heating and then dropped slowly during tempering. Within two hours of tempering, the moisture gradients were reduced to less than 5% of their value at the start of tempering. Similar dissipation of MMG during tempering was also observed by Steffe and Singh[25] and Yang et al.[5] Tempering of four hours, a widespread practice in the rice industry, was found to be more than enough for dissipating the moisture gradients. MMG in any drying pass kept becoming smaller with each subsequent drying pass. Such decline in MMG is mainly due to decrease in the MC of rice kernel in each subsequent pass.

Role of Shrinkage on Drying Curve Prediction

Rough rice grains lose moisture during drying and shrink in size. Such shrinkage in rice kernel dimensions was observed to be proportional to its moisture.[9,10] In most cases, change in kernel dimensions is small. For example, when rice kernels are dried from initial MC of 33% to final MC of 15% (on d.b.), corresponding changes in dimensions are less than 5%. Therefore, most rice drying models (including developed in the current study) do not consider such changes in dimensions during simulations to avoid complexity associated with implementing moisture-dependent model boundaries.

In this study, an alternative approach has been taken to estimate the impact of change in size of rice grain on the drying characteristics. Three separate ellipsoid-shaped models, each having different rough rice sizes (small, normal, and large), were developed. In addition to "normal" size rice that has dimensions of rough rice (M206 variety at 18% MC), dimensions of "small" and "large" size rice grains were obtained by decreasing and increasing kernel dimensions of "normal" rice by 5%, respectively. In each of the three models, kernel dimensions remained the same throughout any drying simulation. By comparing drying curves of these three models, maximum error due to neglecting shrinkage in drying models could be estimated. Drying curves obtained using the three models are shown in Figure 7.

Compared to rice grains of "normal" size, rice grains of smaller size dried faster. In 20 min of drying, MR of small, normal, and large grain rice kernels were 22%, 21%, and 20%, respectively. Change in rice kernel dimensions by 5%, attributed to change of 1% in MR, which would correspond to 0.1–0.3% of MC (on d.b.), depending upon the exact drying conditions. On a moisture loss basis, maximum error caused by neglecting shrinkage was less than 5% of total moisture loss during any drying period between 0 and 90 min. In most drying conditions, change in size of rice dimensions would be smaller than 5% and, therefore, its impact on prediction of drying curves would be even lower. Results in this section justify validity of the assumption to neglect shrinkage in rice drying models.

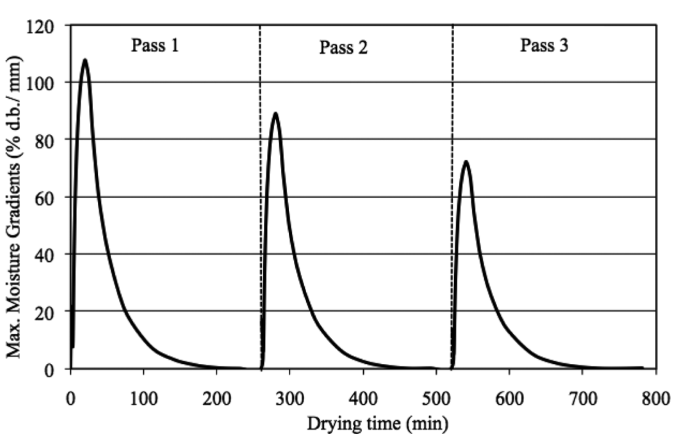

FIG. 6. Maximum moisture gradients (MMG) during multipass heated air drying at 45°C in the ellipsoid-shaped model.

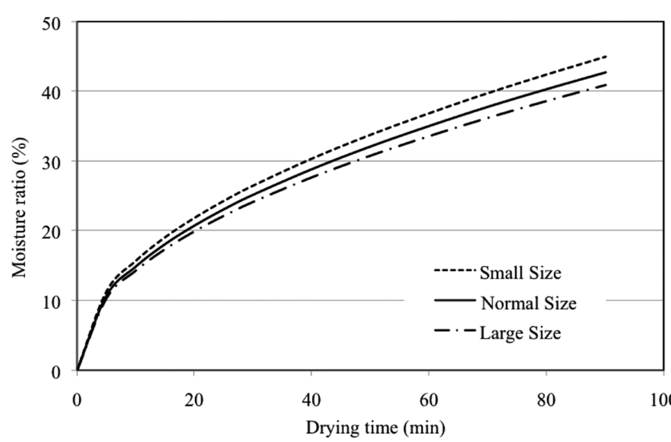

FIG. 7. Drying curves of rice grains of three sizes during heated air drying at 45°C.

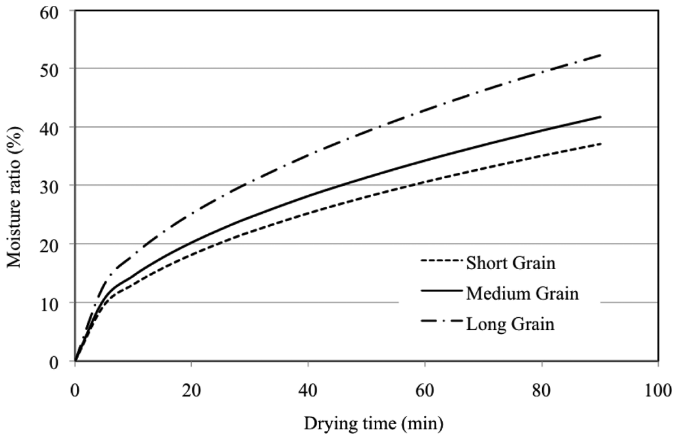

FIG. 8. Drying curves of three Californian rice varieties, short grain S102, medium grain M206, and long grain L206, during heated air drying at 45°C.

Drying Curves of Rice Varieties of Three Grain Types

To determine drying characteristics among rice grains of different varieties, three ellipsoid-shaped mathematical models were developed to determine drying curves in three Californian rice varieties, namely S102, M206, and L206 of short, medium, and long grain rice types, respectively. Length-width ratios in milled rice grains of these rice varieties are 1.7, 2.2 and 3.5, respectively. In reality, physical and hygroscopic properties of these rice varieties might be different. However, to emphasize the impact of only geometry (shape and size), the same rice properties were assumed in the three models. Diffusivity values for endosperm, bran, and husk in all three models were considered the same and equal to that of Californian M206 variety. Drying curves of these rice grains were obtained using the models and are shown in Figure 8.

Predicted drying curves were very sensitive to the grain type. In 20 min of drying, MR of short, medium, and long grain rice kernels were 18%, 20%, and 25%, respectively. Among the three rice grain types, long grain rice has the fastest drying. Such rapid drying is due to its higher exposed surface area to volume ratio. For the short, medium, and long grain rice kernels, surface area to volume ratio were 1677, 1876, and 2354 m^{-1}, respectively. These results emphasize the importance of accurate shape and size considerations and the need for development of separate mathematical models for each rice variety.

CONCLUSIONS

Selecting appropriate shape to represent rice kernels in the mathematical models is essential for making reliable predictions of drying characteristics. In this study, we developed mathematical models considering rice kernel to be of sphere, spheroid, and ellipsoid shape. These three models were used to predict and compare moisture content (MC) and moisture gradients (MG). Impact of grain type and shrinkage on drying curves were also determined. The following conclusions can be drawn from this research:

1. Predictions of MC were similar for spheroid- and ellipsoid-shaped models; however, the sphere-shaped model predicted a slower drying.
2. Magnitude and onset of peak of maximum moisture gradient (MMG) were different in the three models. Magnitude of MMG peak during identical drying conditions was in this order: Ellipsoid > Spheroid > Sphere. The ellipsoid-shaped model predicted the earliest onset of MMG peak, while the spheroid-shaped model predicted the latest.
3. Compared to simpler-shaped models, the ellipsoid-shaped model that closely resembles geometry of the rice grain is preferable in application in rice fissuring research.
4. Two hours of tempering were found to be sufficient to reduce the MMG to less than 5% of its value before tempering for the examined conditions.
5. Impact of shrinkage of rice grains during drying on model predictions is very small. Maximum error in prediction of moisture loss during any drying simulation attributed to neglecting shrinkage would be less than 5% of total moisture loss value.
6. In addition to physical and hygroscopic properties, shape and size of any rice variety also affect the drying characteristics.

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