ABSTRACT. Industrial-scale cross-flow dryers are commonly equipped with grain inverters to improve the uniformity of drying across the column thickness. While a few mathematical models have been reported that include the operation of grain inverters, such models were rarely validated with experiments comprising grain inversions. In this study, a mathematical model was developed to evaluate the impact of grain inverters on the uniformity of grain moisture content (MC) across the column in cross-flow dryers. To improve the accuracy of model predictions, the impact of using two thin-layer drying equations, the Newton and modified Page equations, in the model was also investigated. An experimental setup was fabricated to simulate grain inversion, and drying experiments were performed to measure rice MC and air temperature across the column thickness, which were then compared with model-predicted values. When the modified Page equation was used in the model, the model predictions matched the experimental observations more closely than when using the Newton equation. The model successfully predicted grain and air properties when 0, 1, and 2 grain inversions were used; the root mean square error between predicted and measured values of rice MC and air temperature were within 0.1 to 0.2 percentage points and 1°C to 4°C, respectively. Grain inversions were shown to improve the uniformity of drying in rice kernels; in the tested drying conditions, a single grain inversion produced more uniform drying than two or more grain inversions in the column. The presented results demonstrate the usefulness of the developed model in investigating the role of grain inversion in cross-flow drying of rice. As such, the model could be readily used to improve dryer design, particularly the number and arrangement of grain inverters, and optimize rice drying operations.

Keywords. Deep-bed drying, Grain inverters, Mathematical modeling, Reversed airflow, Thin-layer drying.

Drying is an important post-harvest operation that affects the shelf-life, milling yield, and overall quality of rice. Dryers of various configurations are used in the rice-producing regions of the world. In the U.S., cross-flow column dryers are the most popular type of rice dryer used at the industrial scale (Rumsey and Rovedo, 2001; Schluterman and Siebenmorgen, 2004). In such dryers, grain flows vertically downward between perforated metallic screens, forming grain columns (fig. 1a). Heated air flows through the grain columns in a direction perpendicular (or “cross”) to that of the grain movement; therefore, such dryers are called cross-flow dryers. In this article, “rice” refers to rough rice (paddy), the unhulled form of the crop, unless specified otherwise.

In cross-flow dryers, depending on the location across the column thickness, rice kernels dry at different rates due to drastically different drying air conditions across the column. Rice kernels closer to the heated-air plenum interact with hotter air and dry faster than kernels positioned away from the plenum, which interact with cooler, more humid air. Due to these differences in drying rates, the difference in moisture content (MC) across a drying column can be significant, observed to be as high as 9.1 percentage points (w.b.) for maize (Bakker-Arkema and Liu, 1997) and 3.6 percentage points (w.b.) for rice (Prakash et al., 2017). Such non-uniformity within cross-flow dryers presents two challenges: underdrying or overdrying of kernels and generation of fissures, which is of paramount importance in the case of rice kernels. To improve the uniformity of drying, industrial-scale cross-flow dryers are often equipped with grain inverters (also called turnflows or grain exchangers) that reverse the position of kernels in the column with respect to the drying airflow (fig. 1b). Alternatively, the dryer column can be divided into several sections, and the direction of airflow can be reversed in each section, producing a similar effect as grain inverters on the uniformity of drying (fig. 1c).

Mathematical modeling is an important research tool to study grain drying. Models can be used to facilitate optimization of drying operation parameters, as well as to evaluate improvements in dryer design, such as the inclusion of grain inverters. While several models have been reported for cross-flow grain dryers (Thompson et al., 1968; Otten et al., 1980; Brooker et al., 1992; Bakker-Arkema and Liu, 1997; Rumsey and Rovedo, 2001), only a few studies have included the operation of grain inverters or airflow reversals in their models (Paulsen and Thompson, 1973; Khatchatourian et al., 2013; Nguyen et al., 2016). Furthermore, reported models have been rarely validated by performing experiments comprising grain inversion or reversed airflow.
Recently, Prakash et al. (2017) reported a cross-flow dryer model that was validated by comparing profiles of grain and air properties across the column thickness in an experimental dryer column. The current study extends this model to include the role of grain inversion in the drying column; an experimental setup was also fabricated to simulate grain inversion in the dryer and was used to validate the developed model.

The lack of accurate thin-layer drying equations has been identified as the key factor that affects the accuracy of deep-bed drying models (Morey and Li, 1984; Brooker et al., 1992). The two-parameter Page and four-parameter Midilli equations are commonly reported to be successful in describing thin-layer drying of rice (Cnossen et al., 2002; Hacihafizoglu et al., 2008; Ondier et al., 2010; ASABE, 2014). However, the presence of two or more interdependent parameters in these equations makes it difficult to quantify the impact of air temperature and RH on these equation parameters (Jayas et al., 1991; Cnossen et al., 2002). Prakash and Siebenmorgen (2018) addressed this problem by developing accurate single-parameter drying equations for contemporary long-grain rice cultivars; the use of such equations is hypothesized to improve predictions of cross-flow dryer models.

The goal of this study was to develop a mathematical model that accurately describes the role of grain inverters in cross-flow drying of rice. First, the impact of using an improved thin-layer drying equation in the dryer model was investigated. Secondly, the model reported by Prakash et al. (2017) was enhanced to describe the rice flow patterns inside cross-flow dryers that certain grain inverters produce. Experiments were then performed to simulate grain inversion in a lab-scale dryer; the measured grain and air properties were used for validation of the model. Finally, the role of grain inverters in affecting the uniformity of MC across the column thickness was measured and evaluated.

**MATERIALS AND METHODS**

**MODEL DEVELOPMENT**

The model developed in this study is very similar to the model presented by Prakash et al. (2017); therefore, only a brief outline and the modifications from the previously reported model are described here. The entire grain column is conceptualized to comprise voxels (or volume elements) that are rectilinearly arranged and are fixed relative to the dryer. The grain and air travel through these voxels during the drying process. A series of moisture and heat transport equations are solved in each voxel to determine the properties of the grain and air leaving the voxel. To solve these equations, knowledge of the inlet conditions of the grain and air entering each voxel is required. Therefore, a specific sequence of voxel computations is employed in this model, which ensures that the inlet properties are known for every voxel in subsequent steps (fig. 2). It should be noted that the sequence shown in figure 2 is different from the sequence reported by Prakash et al. (2017); this variation was necessary to account for the grain flow patterns produced by grain inverters.

When rice kernels encounter the grain inverter in the column, the position of the rice kernels is assumed to instantly switch in the thickness direction, i.e., in the x-direction in figure 2a. For example, rice kernels entering the column in voxel 1 travel through the voxels 6, 11, and 16 and then encounter the grain inverter, which switches the grain position so that these kernels enter voxel 25. Similarly, the grain inverter forces kernels leaving voxel 17 to enter voxel 24, kernels leaving 18 enter 23, kernels leaving 19 enter 22, and kernels leaving 20 enter 21. Two representative voxels are shown in figure 1.
The mathematical model was developed and solved in the MATLAB computation environment (ver. R2015b, The MathWorks, Inc., Natick, Mass.). For all model simulations, the voxel thickness (Δx) was selected to be 12.7 mm and the grain duration in a voxel (Δt) was 60 s. Because the grain column was assumed to be 381 mm thick, the number of voxels along the column thickness was 30 in all simulations. The number of voxels along the column height depended on the drying duration; for example, a simulation with a 90 min drying duration had 90 voxels along the column height, while a simulation with a 15 min drying duration had 15 voxels along the column height. Decreasing Δx or Δt did not produce any significantly different model predictions; therefore, the selected values were deemed appropriate for the simulation runs. The computation time was typically less than 5 s on a desktop computer (Dell, Intel i7-4790 CPU, 3.60 GHz, 16 GB memory).

LABORATORY DRYER

Prakash et al. (2017) illustrated the conceptual equivalence between a continuous-flow, cross-flow dryer and stationary-bed dryer and simulated cross-flow drying using a laboratory-scale, stationary-bed dryer; a similar dryer setup was used in this study to validate the model. Drying air of the desired temperature and RH was produced by a 0.91 m³ controlled-environment chamber (Espec North America, Inc., Hudsonville, Mich.) using in-built electrical heating, refrigeration, and control components (fig. 3). A 0.56 kW centrifugal fan (Dayton Electric Manufacturer Co., Chicago, Ill.) was mounted outside the chamber to avoid high-temperature exposure. The fan suctioned air from the chamber and forced it through the grain in the drying bed via insulated air ducts.

The dryer assembly inside the controlled-environment chamber comprised a wooden box and a cylindrical acrylic-glass sample holder that served as the drying column. The wooden box served as a plenum, and the air properties therein were measured to represent the inlet air conditions to the rice column. The sample holder was comprised of three detachable components: a main component that held the grain, a perforated metallic disc, and a top component that resembled the lower part of the main component (fig. 3c). During a drying experiment, rice was first placed in the main component of the sample holder, and the perforated metallic disc placed over the rice. The top component was then placed on the main component and secured using the screw knobs. An O-ring ensured an airtight fit between the sample holder and the wooden box flange. The design of the sample holder allowed it to be detached and flipped such that the grain column could be reversed with respect to the airflow, allowing experimental simulation of grain inversion in the lab dryer.

Six fiber-mesh woven pouches were used to hold rice kernels, approximately 40 g in each pouch; this rice was taken from the same lot as that used to fill the sample holder. These pouches were placed at six equidistant locations (0, 76, 152, 229, 305, and 381 mm from the plenum) within the grain column during filling of the sample holder. The use of these pouches facilitated collection of rice samples from specific

2b to demonstrate the flow patterns and resulting input grain and air conditions before and after the grain inverter.

In addition to the Newton equation used by Prakash et al. (2017), a modified form of the Page equation was also used in the current model version. The Newton-type equation is given by:

\[
\frac{M - M_e}{M_i - M_e} = \text{MR} = \exp(-kt) \tag{1}
\]

\[
k = -8.088 \times 10^{-5} + (5.050 \times 10^{-6})T \tag{2}
\]

where \(M\) is the instantaneous MC of the grain (dec. d.b.), \(M_e\) is the equilibrium MC of rice (dec. d.b.), \(M_i\) is the initial MC of the rice (dec. d.b.), MR is the dimensionless moisture ratio (dec.), \(t\) is the drying duration (min), and \(k\) is an experimentally determined drying constant that depends on the temperature of the drying air \((T, \degree C)\). The equilibrium MC of the grain corresponding to given temperature \(T\) and relative humidity (RH, %) air conditions was determined using the Chung-Pfost equation (ASABE, 2012) with parameters obtained by Ondier et al. (2011):

\[
M_e = \frac{0.01}{0.2316} \times \ln \left[ \frac{-511.7649}{(T + 22.1226) \times \ln (0.01 \times \text{RH})} \right] \tag{3}
\]

The modified Page equation for long-grain rice was given by (Prakash and Siebenmorgen, 2018):

\[
\frac{M - M_e}{M_i - M_e} = \text{MR} = \exp(-kt^{0.52}) \tag{4}
\]

\[
k = -(9.93 \times 10^{-3} + (5.07 \times 10^{-4})T + (1.17 \times 10^{-3})\text{RH} + (2.04 \times 10^{-5})T^2 - (1.23 \times 10^{-5})\text{RH}^2 - (1.00 \times 10^{-5})(T \times \text{RH}) \tag{5}
\]
locations within the column after the completion of a drying run; these rice samples were used for measurement of rice MC.

Six holes of 3.2 mm diameter were drilled in the sample holder through which K-type thermocouples (Omega Engineering, Inc., Stamford, Conn.) were inserted to measure the air temperature at these locations within the grain column; these locations corresponded to the locations of the woven pouches. A seventh thermocouple was inserted into the wooden box to measure the plenum air temperature. All seven thermocouples were connected to an external datalogger (CR300, Campbell Scientific, Inc., Logan, Utah). A miniature, standalone temperature and humidity datalogger (MicroRHTemp, MadgeTech, Inc., Warner, N.H.) was also placed midway inside the grain column (fig. 3a). Another datalogger (HOBO UX100-011, Onset Computer Corp., Bourne, Mass.) was placed at the top of the grain column to measure exhaust air conditions.

RICE SAMPLES
Rice of long-grain cultivar Roy J was used for all drying experiments. The rice was harvested at the University of Arkansas Rice Research and Extension Center near Stuttgart, Arkansas, at approximately 18% MC (w.b.) in 2017. The rice was cleaned using a dockage tester (XT4, Carter-Day, Minneapolis, Minn.) to remove foreign material and unfilled kernels and then stored at approximately 4°C in plastic containers prior to the drying experiments. While all rice used in this study was from the same lot, the rice MC changed slightly during storage, producing different initial MCs during the drying experiments.

DRYING EXPERIMENTS
Three experiments were performed in the lab dryer to validate the model; each experiment consisted of several drying runs with various drying conditions (table 1). Experiment 1 was conducted to compare the performance of the model using the Newton-type and the modified Page-type thin-layer drying equations. Rice was dried for five durations while not performing any grain inversion. This comparison was then used to select the better thin-layer drying equation, which would be used in the model for all further analyses in this study.

The second and third experiments were both performed to validate simulation of grain inversions in the model. Two different plenum air conditions, 60°C - 10% RH and 45°C - 20% RH, were used in the second and third experiments, respectively. Both selected plenum air conditions had the same humidity ratio of 0.012 kg of water per kg of dry air; this humidity ratio is common for ambient air during the rice drying season in the mid-south U.S. The data from the second and third experiments were also used to evaluate the impact of grain inversions on the uniformity of grain MC across the column thickness.

For all drying runs involving grain inversion, the total drying duration was 60 min. For no grain inversion, the rice was dried continuously for 60 min. For a single grain inversion, the grain column orientation was reversed after 30 min into the drying runs. For two inversions, the orientation of the column was reversed once at 20 min and again at 40 min to model two grain inverters in a column. The order of drying runs in each experiment was randomized. All corresponding measurements of grain and air properties obtained from the duplicate drying runs performed at given drying conditions were averaged for subsequent analyses.

Prior to any drying run, rice was taken from the refrigerated storage and equilibrated to room temperature in closed

<table>
<thead>
<tr>
<th>Condition</th>
<th>Experiment 1</th>
<th>Experiment 2</th>
<th>Experiment 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial rice MC (% w.b.)</td>
<td>17.6 (0.1)</td>
<td>17.2 (0.1)</td>
<td>16.8 (0.1)</td>
</tr>
<tr>
<td>Initial rice temperature (°C)</td>
<td>26 (1)</td>
<td>25 (2)</td>
<td>22 (1)</td>
</tr>
<tr>
<td>Plenum air temperature (°C)</td>
<td>60</td>
<td>60</td>
<td>45</td>
</tr>
<tr>
<td>Plenum air RH (%)</td>
<td>10</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Drying duration (min)</td>
<td>15, 30, 45, 60, 90</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>No. of grain inversions</td>
<td>0, 0, 1, 2</td>
<td>0, 1, 2</td>
<td>0, 1, 2</td>
</tr>
<tr>
<td>No. of replicate drying runs</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total number of drying runs</td>
<td>5 × 2 = 10</td>
<td>3 × 2 = 6</td>
<td>3 × 2 = 6</td>
</tr>
</tbody>
</table>

Numbers in parentheses are standard deviations of measured values for the various drying runs in an experiment.
plastic bags; 2910 g of rice was used in each drying run. Approximately 40 g of rice was placed in each of the six woven pouches. The miniature datalogger, pouches, and remaining rice were carefully placed in the sample holder so that the datalogger was located at mid-height, i.e., 190 mm from the air plenum. The drying column thus formed in the sample holder was of cylindrical shape with a diameter of 127 mm and height of 381 mm. To perform grain inversion, the sample holder was raised from the wooden box, flipped vertically, and then refitted to the wooden box; the time required to perform a grain inversion was approximately 10 s. After completion of the drying runs, the rice in the sample pouches was stored in sealed plastic bags at ambient conditions (22°C to 26°C) before subsequent measurement of MC using an oven method.

For all drying runs, the airflow rate through the rice was 0.53 m³ s⁻¹ m⁻², which was measured with a vane-type anemometer (HHF141, Omega Engineering, Inc., Stamford, Conn.). The experimental setup allowed continuous measurement of air temperature at six locations in the grain column. However, the grain MC at these six locations, i.e., in each of the six pouches, could be measured only once, at the end of a drying run. The MC of the rice was determined by drying a 15 g sample for 24 h in a convection oven, which was operated at 130°C (Jindal and Siebenmorgen, 1987).

Model simulations were run for every drying condition of the three experiments, and the root mean square error (RMSE) was determined to quantify the accuracy to which the model predicted the experimental data:

\[
RMSE = \sqrt{\frac{\sum_{n=1}^{N} (X_m - X_e)^2}{N}}
\]

where \(X\) is the grain or air property being compared, and \(N\) is the number of compared data points measured across the grain column. The subscripts \(m\) and \(e\) indicate whether the property was determined from the model or experiments. It should be noted that each \(X_e\) is an average of two measurements obtained from the duplicate drying runs performed in identical drying conditions; using the average value reduces experimental errors, and thus provides a better estimate of the true grain or air property for comparison with the model-predicted value during RMSE calculation. Because the experimentally determined values of rice MC and air temperature were measured at six locations in the rice column, the value of \(N\) was 6 for all reported RMSEs, except for air temperatures in experiment 1. For experiment 1, the air temperature was not measured at the 0 mm location from the plenum; therefore, \(N\) was 5 while calculating the corresponding RMSEs.

**RESULTS AND DISCUSSION**

**COMPARISON OF THIN-LAYER DRYING EQUATIONS**

For each drying condition of experiment 1 (table 1), two sets of model simulations were run. The simulation sets differed in the selection of the thin-layer drying equation used in the model. One set used the Newton equation (eqs. 1 and 2), while the other set used the modified Page equation (eqs. 4 and 5). The rice MC and air temperature profiles predicted from these simulations were compared with experimental measurements to evaluate the model performance using each thin-layer drying equation (figs. 4 and 5). It should be noted that rice at the end of a drying run in the lab dryer was equivalent to rice exiting a cross-flow dryer column in the model. Figures 4 and 5 clearly show that the model predictions match the experimental measurements more closely when the modified Page equation was used in the model. While Noomhorm and Verma (1986) and Nguyen et al. (2016) evaluated the role of thin-layer drying equations in deep-bed rice dryers, the equations they evaluated were different from those used in the current study; therefore, the presented results could not be corroborated with their work. To quantify and compare the accuracy of model predictions of grain and air properties, the RMSEs were determined when using each thin-layer drying equation in the model (table 2).

![Figure 4](image-url)

**Figure 4.** Comparison of rice moisture content profiles within a grain column, as predicted by a mathematical model and measured experimentally, after drying for the three indicated drying durations. Each experimental data point is the average of two drying run replications. Model simulations were run using two thin-layer drying equations: (a) the Newton equation (eqs. 1 and 2) and (b) the modified Page equation (eqs. 4 and 5). For these drying runs, the plenum air conditions were 60°C and 10% RH, and the initial MC of rice was 17.6% (w.b.).
Experiment - 15 min
Experiment - 15 min
Experiment - 90 min
Experiment - 90 min
Experiment - 45 min
Experiment - 45 min
Experiment - 45 min

after drying for the three indicated durations. Each experimental data point is the average of two drying run replications. Model simulations were run using two thin-layer drying equations: (a) the Newton equation (eqs. 1 and 2) and (b) the modified Page equation (eqs. 4 and 5). For these drying runs, the plenum air conditions were 60°C and 10% RH, and the initial MC of rice was 17.6% (w.b.).

Table 2. Root mean square errors (RMSE) between predicted and experimental grain and air properties after five drying durations in experiment 1 (table 1) when the Newton and modified Page equations were used in the dryer model.

<table>
<thead>
<tr>
<th>Drying Duration (min)</th>
<th>Rice MC (percentage points, w.b.)</th>
<th>Air Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Newton</td>
<td>Modified</td>
</tr>
<tr>
<td>15</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>30</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>45</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>60</td>
<td>0.8</td>
<td>0.1</td>
</tr>
<tr>
<td>90</td>
<td>1.4</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The magnitudes of the RMSEs obtained in this study, especially when the Newton equation was used in the model, are similar to those of Prakash et al. (2017), who obtained RMSEs of rice MC and air temperature of 0.6 to 0.9 percentage points and 3°C to 5°C, respectively. When the modified Page equation was used in the dryer model, lesser RMSEs were obtained for both MC and air temperature predictions, demonstrating that using an improved thin-layer drying equation accrues benefits that contribute to the overall accuracy of the dryer model. The presented results reconfirm the need to develop accurate thin-layer drying equations for each grain being modeled.

SIMULATION OF GRAIN INVERTERS IN DRYER MODEL

For each drying condition in experiments 2 and 3 (table 1), model simulations were run using the modified Page equation in the model. To validate the model when simulating the use of grain inverters in the drying column, a comparison of model-predicted and experimentally measured rice MC and air temperature profiles is presented in figures 6 and 7, respectively. For the air temperature profiles in figures 7a and 7b, drying durations of 35 and 45 min were selected, respectively; the selected durations demonstrate the air profiles 5 min after performing grain inversions in each drying run.

For the tested drying conditions, the model accurately predicted grain MC (fig. 6). However, the model slightly underpredicted the air temperatures (fig. 7); the difference between the model-predicted and experimentally measured air temperature was generally less than 5°C. Such underprediction of air temperature, particularly at locations in the grain column that were distant from the heated-air plenum, was also observed in figure 5b and was probably due to errors associated with the thin-layer drying and moisture isotherm equations in the model. The parameters of both of these equations were determined based on experiments in which the air RH was in the 10% to 72% range; therefore, using these parameters beyond this range could produce errors. It should be noted that air RH in a few locations in the drying column was measured to be as high as 90% during the drying runs performed in this study.

The RMSEs between the predicted and experimental grain MC and air temperatures at different drying durations are listed in table 3. The magnitude of the RMSEs for rice MC and air temperature was 0.1 to 0.2 percentage points and 1°C to 4°C, respectively. The high accuracy of the model predictions could be attributed to the use of an accurate thin-layer drying equation, as well as the design of the sample holder and dryer assembly that allowed well-controlled experimental simulation of grain inversions. The accuracy of the model could be potentially further improved by using moisture isotherm and thin-layer drying equations that are valid for a wider range of air conditions (temperature and RH), as well as for contemporary rice cultivars. Furthermore, in commercial cross-flow dryers, harvested rice is typically commingled (mixture of several rice cultivars), plenum airflow into the rice column is often non-uniform, and grain inverters usually do not produce complete inversion of the rice kernels across the column. These factors might produce additional deviations between model predictions and the actual performance of a dryer; therefore, model validation at commercial-scale dryers is suggested.
Table 3. Root mean square errors (RMSE) between predicted and experimental grain and air properties at specified drying durations for the conditions listed in experiments 2 and 3 (table 1). GI refers to the number of grain inversions performed in the drying runs.

<table>
<thead>
<tr>
<th>Drying Duration (min)</th>
<th>Experiment 2</th>
<th>Experiment 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 GI 1 GI 2 GI</td>
<td>0 GI 1 GI 2 GI</td>
</tr>
<tr>
<td>Rice MC (percentage points, w.b.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.1 0.2 0.2</td>
<td>0.1 0.2 0.1</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>15 30 45 60</td>
<td>15 30 45 60</td>
</tr>
<tr>
<td>15</td>
<td>3.1 3.2 2.7</td>
<td>1.1 1.7 1.7</td>
</tr>
<tr>
<td>30</td>
<td>2.3 1.4 2.4</td>
<td>2.1 1.7 2.0</td>
</tr>
<tr>
<td>45</td>
<td>2.3 2.1 3.2</td>
<td>1.3 1.7 1.2</td>
</tr>
<tr>
<td>60</td>
<td>2.2 2.1 3.1</td>
<td>1.3 1.7 1.2</td>
</tr>
</tbody>
</table>

**UNIFORMITY OF DRYING**

The primary purpose of using grain inverters is to facilitate more uniform drying of kernels in the drying column. In this study, such uniformity of drying was quantified by the range of rice MC across the column thickness. Because rice MC was measured from the sample pouches at six locations in the grain column, the range of MC was calculated as the difference between the maximum and minimum of these six measured MCs and expressed as percentage points on a wet basis.

The range of rice MCs after the drying runs of experiments 2 and 3 is shown in figure 8. While a single grain inversion was observed to be beneficial in reducing the range of MCs, performing two grain inversions was counterproductive. Similar observations were reported for commercial rice dryers by Schlutermann and Siebenmorgen (2004); rice MC across the column was less uniform after the second grain inversion than after the first. While simulating airflow reversals in cross-flow drying of soybeans, Khatchatourian et al. (2013) reported a similar phenomenon; switching the airflow direction once resulted in more uniform drying of kernels than switching the airflow direction twice. Such observations could be explained based on differences in the duration at which rice kernels dry at the original and inverted locations in the column. When rice kernels spend an equal drying duration in both the original and inverted positions,
as observed in a single grain inversion, more uniform drying is expected. However, when performing two grain inversions in the column, rice spends 2/3 of the total drying duration in the original position and only 1/3 in the inverted position.

While limited experimentation was performed to evaluate the effect of the number of grain inversions on the uniformity of drying, the model was used to predict the range of MCs across a grain column that could be expected for greater numbers of grain inversions. Figure 9 shows the model-predicted range of MCs in the drying conditions listed for experiment 2 in table 1. The model was run using the more accurate, modified-Page thin-layer drying equation.

Similar to the trends observed from the experimental measurements, figure 9 shows that a single grain inversion was more effective in reducing the range of MCs than using two or more grain inversions in the column. Considering the practical significance of these results, more research is needed to ensure that the phenomenon is consistent across the full range of rice and air conditions that may exist in a commercial dryer. Furthermore, the milling quality of rice needs to be evaluated before making any recommendation to the rice industry.

CONCLUSIONS

A mathematical model was developed to predict grain and air properties throughout the grain column in a cross-flow dryer. Additionally, the model was enhanced to simulate the operation of such a dryer with grain inverters installed. An apparatus was fabricated that included a reversible sample holder to facilitate simulation of grain inversions in a lab-scale dryer. Drying experiments were performed to validate the mathematical model and to measure the impact of grain inversions on the uniformity of drying across a rice drying column.

Application of two thin-layer drying equations in the model was also investigated. When the modified Page equation was used in the model, the model predictions matched the experimental observations more closely than when using the Newton equation. The RMSEs between the predicted and measured values of rice MC and air temperature were within 0.1 to 0.3 percentage points and 1°C to 2°C, respectively, when using the modified Page equation in the model. Results presented in this study reconfirm the need for using accurate thin-layer drying equations in grain drying models.

The model successfully predicted grain and air properties when grain inversion was used. The RMSEs between predicted and measured values of rice MC and air temperature were within 0.1 to 0.2 percentage points and 1°C to 4°C, respectively. As such, it is proposed that the model could be readily used to improve dryer design (particularly the number and arrangement of grain inverters) and optimize grain drying operations when using cross-flow dryers. The use of grain inversion improved the uniformity of rice MCs across the drying column. In the tested drying conditions, a single grain inversion was more successful in improving the uniformity of MC than two or more grain inversions in the column.

The current study presented two research tools, a mathematical model and a lab-scale dryer setup, to evaluate the role of grain inverters in a cross-flow drying operation. With minor modifications, the presented model could also be used to describe flat-bed rice dryer operation using reversed airflow.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support by the corporate sponsors of the University of Arkansas Rice Processing Program and the Arkansas Rice Research and Promotion Board.

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