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# Low-temperature, low-relative humidity drying of rough rice

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ABSTRACT

The use of low air temperatures (26–34 °C) and relative humidities (19–68%) to dry thin-layer samples of rough rice to the desired 12.5% moisture content was investigated. Drying rates and durations and their effects on the quality parameters of head-rice yield, color, and pasting viscosity of long- and medium-grain rice cultivars harvested at 19.6% and 17.5% moisture contents, respectively, were determined. Results showed that dehumidification of the drying air had greater potential for increasing drying rates at 26 °C than at 30 and 34 °C. Low drying air temperatures and relative humidities had no adverse effects on head-rice yield or color compared to controls. Peak and final viscosities of low-temperature and low-relative humidity dried samples were similar to controls.

## 1. Introduction

Rice constitutes the staple food for a large proportion of the world's population (Evanson et al., 1996), and its consumers represent one of the most demanding cereal markets with regards to product quality. Kernel quality is thus of utmost importance to the rice processing industry. Two of the main indices used to determine rice quality are head-rice yield (HRY) and head-rice color. Head-rice yield is accepted as the current measure of commercial physical quality and is defined as the mass percentage of rough rice kernels that remains as head-rice (kernels that are at least 3/4 of the original kernel length) after complete milling. Other frequently reported rice quality parameters include pasting properties, chemical properties, and sensory quality (Daniels et al., 1998; Meullenet et al., 1999; Pearce et al., 2001; Perdon et al., 2001; Ranalli et al., 2003; Zhou et al., 2003).

Post-harvest management of rice plays an essential role in maintaining rice quality. Rough rice is normally harvested at moisture content (MC[1]) ranging from 14% to 26%. High-MC rice kernels are subject to elevated respiration rates due to enzyme activity and mold growth (Dillahunty et al., 2000), which reduce the dry matter content of rice and may produce sufficient energy to be detrimental to product quality (Bradburn et al., 1993). It is generally considered that under typical storage environments, the MC of rough rice must be reduced to less than 13% for safe long-term storage.

The commercial rice drying industry uses heated air in different drier designs (Inprasit and Noomhorm, 2001). Column and cross-flow dryers generally operate at 45–78 °C (Calderwood, 1975; Hogan and Karon, 1955). Some multi-stage driers have been reported to operate at temperatures as high as 80–200 °C (Inprasit and Noomhorm, 2001). Rapidly drying rough rice using such high temperatures may lead to kernel fissuring and eventual breakage during milling (Inprasit and Noomhorm, 2001). Bonazzi et al. (1997) showed that rough rice quality can be adversely affected if air with high evaporative capacity is used for drying. Kunze and Calderwood (1985) suggested that the drying rate, more so than the drying air temperature, determines final rice quality.

High temperature drying establishes a MC gradient between the surface and the center of the kernel due to evaporation from the outer layers of the kernel (Siebenmorgen et al., 2004). The MC gradient results in tensile and compressive stresses within the kernel, which if sufficiently large, provoke kernel fissuring and breakage (Ban, 1971; Kunze and Choudhury, 1972; Sharma and Kunze, 1982; Nguyen and Kunze, 1984; Abud-Archila et al., 2000; Cnossen et al., 2003).

Various steps must therefore be undertaken to preserve kernel quality when drying rough rice at fast rates, typically associated with high temperatures. Tempering procedures, whereby rice is held in bins at constant temperature for given durations between drying passes, are employed in commercial drying to allow intra-kernel MC gradient reduction (Calderwood, 1975). Tempering thus results in a more uniform moisture distribution within the kernel

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[1] Unless otherwise specified, all moisture contents are reported on a wet-basis.

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by facilitating moisture diffusion from the core to the surface (Cihan and Ece, 2001).

High temperature drying systems are, however, not optimal for farm level drying situations due to time constraints and lack of skilled personnel to monitor drier operations. There is, therefore, a need to develop appropriate on-farm rough rice drying methods. One alternative is the use of low drying air temperatures and RHs. Current drying methods that employ low drying air temperatures include solar drying and natural air bin-drying.

Low-temperature, low-RH drying is similar to heated air grain drying but does not involve heat to lower the RH of the drying air. In contrast, the RH is decreased by other means such as circulation through a desiccant material, which adsorbs/removes moisture from the drying air.

Few studies have focused on the use of low drying air temperature and the impact it has on product quality. Cihan et al. (2007a,b) developed a diffusion-based model describing intermittent drying of thin-layer rough rice at 40 °C. Iguaz et al. (2002) conducted thin-layer drying experiments using air at 30–35 °C and found that temperature had a greater influence on the drying rate than RH, and air velocity had a significant influence on the drying rate when drying air temperature was low (<30 °C). Kahveci et al. (2002) developed a theoretical model for predicting drying kinetics of rough rice over a wide range of drying conditions and reported temperature as the main factor influencing rough rice drying. Basunia and Abe (1998) found the Page equation to be suitable for describing thin-layer drying characteristics of freshly harvested rough rice dried under natural convection with air temperature and RH ranging between 22.3–34.9 °C and 34.5–57.9%, respectively. Similar findings have been reported by Dung et al. (1980), Cihan (1991), and Jayas et al. (1991).

The objectives of this experiment were to: (1) establish drying curves and equilibrium moisture contents (EMCs) of thin-layer rough rice dried using low-temperature and low-RH air, (2) determine differences in drying rate that result from varying temperatures and RHs when EMC is kept constant, and (3) analyze the effect of these drying conditions on rice quality, specifically, HRY, color, and pasting viscosities.

## 2. Materials and methods

In the fall of 2008, Wells (long-grain) and Jupiter (medium-grain) rice cultivars were harvested from Stuttgart, AR at 19.6% and 17.5% MC, respectively. All lots were cleaned using a dockage tester (XT4, Carter-Day Co., Minneapolis, MN) and stored in 32-gallon (0.14 m$^3$) plastic bins at 5 °C for 12 weeks. The MC of each lot was determined after harvesting and before storage by drying duplicate, 15-g samples in a convection oven (1370 FM, Sheldon Inc., Cornelius, Oregon) maintained at 130 °C for 24 h (Jindal and Siebenmorgen, 1987).

The drying apparatus (Fig. 1) consisted of two major parts: an air conditioning control unit and a drying chamber. The air conditioning unit (Parameter Generation and Control Chamber, Black Mountain, NC) was used to generate drying air at low-temperature and low-RH. The drying chamber included 16 removable trays (15 × 25 cm), eight on each side. The air conditions in the drying chamber were monitored by a dew point hygrometer (Hygro-MZ, General Eastern, Woburn, MA).

The Modified Chung-Pfost equation (Eq. (1)) was used to predict EMCs (7.5%, 10.0%, and 12.5%) for different combinations of temperature (26, 30, and 34 °C) and RH (19–68%). The experimental approach was designed to determine differences in drying rate that result from varying temperatures and RHs when EMC is kept constant, as well as to evaluate the effectiveness of the Modified Chung-Pfost equation in predicting EMC.

$$M_e = \frac{-1}{C}\,\mathrm{Ln}\left[\frac{-(T+B)\mathrm{LnRH}}{A}\right] \tag{1}$$

where, $M_e$ is the equilibrium moisture content, % dry-basis, $T$ is the temperature in °C, RH is the relative humidity in decimal, and $A$, $B$, and $C$ are grain-specific empirical constants (ASABE, 2007).

Thin-layer drying experiments were conducted for each of the following conditions; 26 °C and 19%, 42%, and 65% RH, 30 °C and 21%, 45%, and 67% RH, and 34 °C and 23%, 47%, and 68% RH to yield estimated 7.5%, 10.0%, and 12.5% rough rice EMCs, respectively (Fig. 2). Before the start of each drying experiment, the air conditioning unit was operated at the test settings for at least 4 h to stabilize the drying air conditions.

Prior to drying treatments, rough rice samples were obtained from cold storage and equilibrated to room temperature in sealed plastic bags for 24 h. This step brought the rice into thermal equilibrium with the room temperature, thereby preventing condensation on the rice when placed in the drying chamber, and eliminated any transient heat transfer effects on rough rice drying rates. After drying air conditions within the drying chamber stabilized, two 200-g samples of rough rice from each cultivar were placed in separate trays on one side of the drying chamber (Fig. 1). Duplicate samples were placed on the opposite side of the drying chamber. Thus, eight trays, each containing 200 g of rough rice, were dried at each test condition.

The drying air, at set temperature and RH, was circulated from the air conditioning unit through perforations at the bottom of each tray containing the rice samples and back to the air conditioning unit. Each tray was weighed every 30 min on an analytical balance with an accuracy of ±0.1 g (Model 8800, Seedboro equipment, Chicago, IL) until there was no significant change in mass (<0.1 g) with successive measurements. This operation was carried out rapidly and it was presumed that such brief interruptions did not interfere with the drying process. Temperature and RH sensors/loggers (H-8 series, 4-channel, Onset Computers, Bourne, MA) were

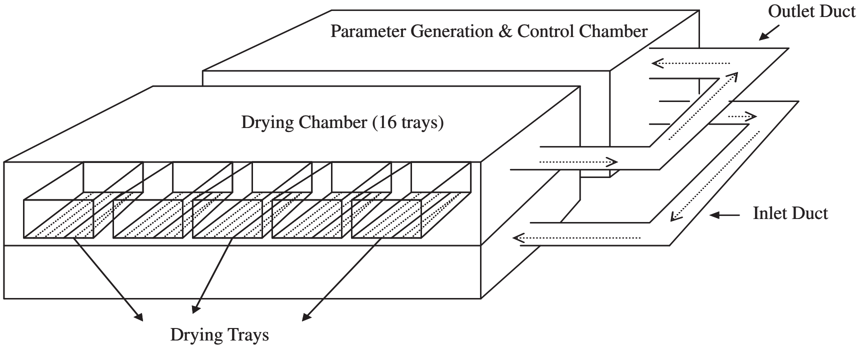

**Fig. 1.** Schematic of the drying unit used to conduct low-temperature and low-relative humidity thin-layer drying experiments.

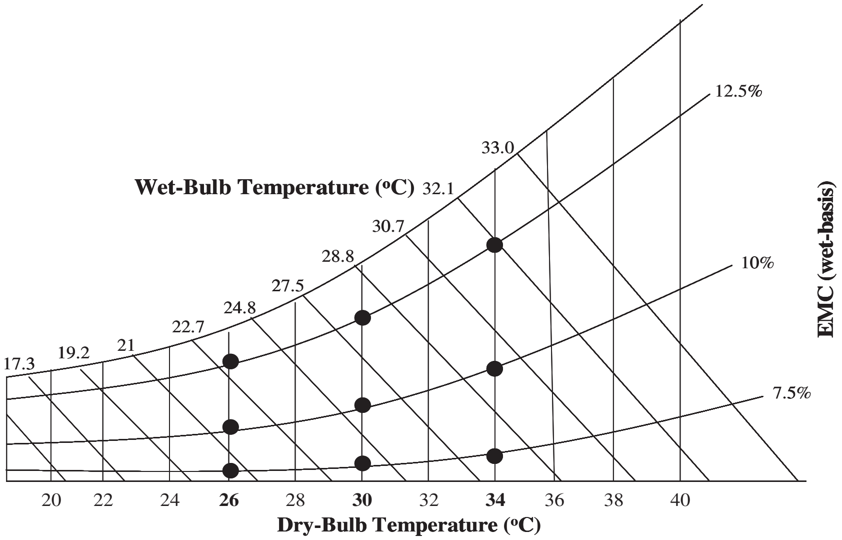

**Fig. 2.** Wet- and dry-bulb temperature combinations that would yield 7.5%, 10%, and 12.5% rough rice equilibrium moisture contents (EMCs). The EMC for each combination of temperature and relative humidity were determined using the Modified Chung-Pfost equation (ASABE, 2007).

placed in the drying chamber to record the temperature and RH of the drying air over a drying duration. At the end of each drying experiment, the final MC of each rice sample was determined using the previously described oven method (Jindal and Siebenmorgen, 1987).

After obtaining drying curves and determining the duration required to reach the desired 12.5% MC, additional thin-layer drying experiments were conducted in which duplicate samples from each cultivar were dried at the test conditions to 12.5% MC. These samples were used for quality assessment.

Quality was assessed in terms of head-rice yield (HRY), color, and pasting viscosity. To determine HRY, duplicate, 150-g subsamples of each sample dried to 12.5% MC were dehulled using a laboratory huller (Satake Rice Machine, Satake Engineering Co., Ltd., Tokyo, Japan), milled in a laboratory mill (McGill #2, Rapsco, Brookshire, TX) for 30 s, and aspirated with a seed blower (South Dakota Seed Blower, Seedboro, Chicago, IL). Head-rice was separated from broken kernels using a double-tray sizing machine (Grainman, Grian Machinery MFG, Miami, FL) and HRY calculated as the mass percentage of rough rice remaining as head-rice.

The whiteness of duplicate, 90-g head-rice sub-samples was determined using a color meter (ColorFLex, Hunter Lab, Reston, VA). Rice whiteness values were determined as a reflective index of the sample surface: the higher the $L^*$ value, the whiter the milled rice.

To determine pasting viscosity, duplicate, 20-g head-rice subsamples were ground into flour using a cyclone mill with a 0.5-mm sieve (Model 2511, Udy Corp., Fort Collins, CO). The MC of the flour was determined by drying duplicate, 5-g samples in a convection oven at 130 °C for 1 h (Jindal and Siebenmorgen, 1987). Peak and final viscosities of the rice flour were determined using a Rapid Visco Analyzer™ (RVA) (Model 4, Newport Scientific, Warriewood, NSW, Australia). Viscosity was measured by mixing 3 ± 0.01 g of flour (at approximately 12% MC) with 25 ± 0.05 ml deionized water. Water corrections were made to account for the samples being above or below 12% MC. The RVA was set up on an 11.5 min runtime (1.5 min at 50 °C, heating to 95 °C at 12 °C/min, 2.5 min at 95 °C, and cooling to 50 °C at 12 °C/min) according to AACC Methods (1996). Peak and final viscosities were recorded in RVA units (1 RVA unit = 10 cP).

All statistical analyses, which included linear and non-linear regression, and analysis of variance, were performed using JMP 8.0.1 software (SAS Institute, Inc., Cary, NC). Statistical significance tests were performed at $\alpha = 0.05$.

## 3. Results and discussion

### 3.1. Drying curves

The Page equation (Page, 1949) was used to describe the drying data using non-linear regression analysis in order to establish the asymptotic EMC, the dimensionless constant $n$, and the drying constant $k$. The drying constant reflects the rate of moisture removal from kernels.

$$\mathrm{MR} = \frac{M - M_e}{M_i - M_e} = e^{-kt^n} \tag{2}$$

where: MR is the moisture ratio, $M_i$ is the initial moisture content, $M$ is the moisture content after a given drying duration, $t$, $M_e$ is the equilibrium moisture content, and $k$ and $n$ are drying constants.

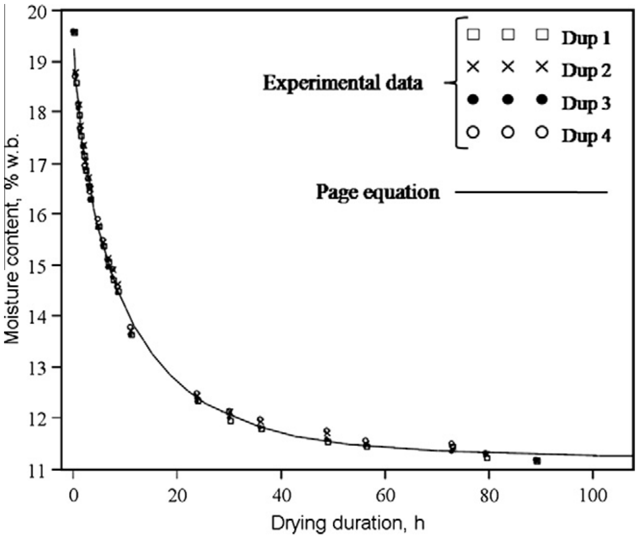

**Fig. 3.** Thin-layer drying data for long-grain Wells rough rice samples dried at 26 °C and 42% relative humidity described using the Page equation (Eq. (2)).

Results showed a high rate of moisture removal at the initial stages of the drying process followed by a gradual leveling of the drying curve (Fig. 3). Similar observations were reported by Ece and Cihan (1993). Drying parameters $n$ and $k$ of the Page equation (Eq. (2)), the *coefficient of determination* ($R^2$), and the corresponding *root mean square error* (RMSE) were determined for each drying curve using non-linear regression (Table 1). For each drying condition and rice cultivar, no significant differences ($p$-value > 0.05) were observed between the four duplicates; hence the average of each was reported. The mean $R^2$ and RMSE for all drying curves were 0.99 and 0.0762, respectively, which indicates that the experimental data were described well using the Page equation. Cihan et al. (2007a,b) and Akal et al. (2007) evaluated the suitability of 12 models for describing thin- and thick-layer drying behavior of rough rice and found the Page equation to be the best among two-coefficient models.

The individual $k$ values could not be compared because $n$ values were found to be significantly different ($p$-value < 0.05) across treatments and for both cultivars. Multiple linear regressions of the individual $k$ and $n$ values were performed to determine the linear, quadratic, and interaction effects of temperature and RH. The linear effects of both temperature and RH on $k$ and $n$ were significant ($p$-values < 0.05), but there was no significant interaction between the two factors ($p$-value > 0.05). From the multiple linear regression, the expressions of $k$ and $n$ as functions of temperature and RH were:

$$k = -0.05303 + 0.0117T(^\circ\mathrm{C}) - 0.0011\mathrm{RH}(\%)$$

With $R^2$ of 0.80 and RMSE of 0.0213.

$$n = 0.6434 - 0.0026T(^\circ\mathrm{C}) + 0.0024\mathrm{RH}(\%)$$

With $R^2$ of 0.70 and RMSE of 0.0293.

### 3.2. Equilibrium moisture content predicted by the Modified Chung-Pfost equation

There were no significant differences ($p$-value > 0.05) between the EMCs of long- (Wells) and medium-grain (Jupiter) samples dried at the same conditions. However, the experimental data were significantly greater ($p$-values < 0.05) than EMCs predicted by the Modified Chung-Pfost equation (Eq. (1)) for all drying conditions (Table 2). The inaccuracy of the isotherm model in predicting EMCs at the tested conditions and for the two rice cultivars was attributed to the empirical values used (ASABE Standards, 2007). Chirife and Iglesias (1978) found most isotherm models to be successful in predicting EMC for a given product at specific range of temperatures and RH. Numerous studies have shown the need to determine empirical values for sorption isotherm models to suit the grain and range of temperatures and RHs under investigation (Iguaz and Versada, 2007; Basunia and Abe, 2001; Chen and Morey, 1989; Sun and Byrne, 1998; Sun and Woods, 1994).

**Table 1**
Drying parameters $k$ and $n$ of the Page equation (Eq. (2)), correlation coefficient, $R^2$, and root mean square error (RMSE) estimated from drying curves obtained for medium-grain Jupiter and long-grain Wells rice samples dried at 26–34 °C and 19–68% relative humidity. Each experimental value is an average of four duplicates.

| Cultivar | Temperature (°C) | RH (%) | $k$ | $n$ | $R^2$ | RMSE |
|---|---|---|---|---|---|---|
| Wells | 26 | 19 | 0.23072 | 0.64036 | 0.99 | 0.06838 |
| | | 42 | 0.20116 | 0.72061 | 0.99 | 0.08700 |
| | | 65 | 0.18950 | 0.73138 | 0.99 | 0.19319 |
| | 30 | 21 | 0.26490 | 0.63656 | 0.99 | 0.09301 |
| | | 45 | 0.26560 | 0.64936 | 0.99 | 0.04414 |
| | | 67 | 0.22034 | 0.74914 | 0.99 | 0.05056 |
| | 34 | 23 | 0.32110 | 0.67944 | 0.99 | 0.05552 |
| | | 47 | 0.29303 | 0.68343 | 0.99 | 0.14442 |
| | | 68 | 0.26550 | 0.78886 | 0.99 | 0.03831 |
| Jupiter | 26 | 19 | 0.21545 | 0.64323 | 0.99 | 0.04918 |
| | | 42 | 0.17836 | 0.73661 | 0.99 | 0.04901 |
| | | 65 | 0.16558 | 0.76579 | 0.99 | 0.01258 |
| | 30 | 21 | 0.25857 | 0.63083 | 0.99 | 0.06174 |
| | | 45 | 0.24649 | 0.65364 | 0.99 | 0.04931 |
| | | 67 | 0.18968 | 0.74335 | 0.99 | 0.05806 |
| | 34 | 23 | 0.29415 | 0.66300 | 0.99 | 0.12625 |
| | | 47 | 0.29358 | 0.69602 | 0.99 | 0.06895 |
| | | 68 | 0.22955 | 0.80685 | 0.99 | 0.05858 |

### 3.3. Drying duration

From the non-linear regression models described by the Page equation (Eq. (2)), the drying durations required to reach the desired 12.5% MC for each drying air condition and rice sample dried were determined as the values on the $x$-axis that corresponded to the desired MC on the $y$-axis (Fig. 4). The drying durations required to reach 12.5% MC were considered the basis for practically comparing the influence of drying air conditions.

At constant drying temperature, the greater the RH of the drying air, the longer the drying duration required to reach 12.5% MC (Table 3). However, the influence of RH on the drying duration was greater at 26 °C than at 30 and 34 °C. For example, at 26 °C, when the RH of the drying air was decreased by 23% points (from 42% to 19%), the drying duration required to reach 12.5% MC for Wells rice samples (initially at 19.6% MC) was approximately 11.7 h less compared to 7.2 h at 30 °C and 4.3 h at 34 °C when the RH was decreased by the same magnitude (Table 3). This shows that dehumidification of drying air has the potential of significantly increasing the drying rate at relatively low-temperatures (<34 °C).

### 3.4. Head-rice yield

The HRY results for Wells and Jupiter samples dried at test conditions to approximately 12.5% EMC are shown in Table 4. The HRYs of the experimental samples were compared to those of control samples dried at 26 °C and 54% RH to approximately 12.5% MC. Results showed no significant differences between HRYs of experimental samples and controls ($p$-value > 0.05). Sugunya et al. (2004) made similar observations where HRYs from rough rice dried with modified air at 30–40 °C was similar to controls. Calderwood (1975) showed that slow drying rates, synonymous with low-temperature drying, does not cause HRY reduction.

**Table 2**
Experimental data and equilibrium moisture content (wet-basis) predicted by the Modified Chung-Pfost equation (Eq. (1)) for rice samples dried at 26–34 °C and 19–68% relative humidity. Each experimental value is an average of four duplicates.

| Predicted EMC (%) | Temperature (°C) | Relative humidity (%) | Experimental data (%)* |
|---|---|---|---|
| 7.5 | 26 | 19 | $8.1^b$ |
| | 30 | 21 | $7.9^a$ |
| | 34 | 23 | $7.8^a$ |
| 10.0 | 26 | 42 | $11.1^b$ |
| | 30 | 45 | $10.5^a$ |
| | 34 | 47 | $10.6^a$ |
| 12.5 | 26 | 65 | $13.8^c$ |
| | 30 | 67 | $13.2^b$ |
| | 34 | 68 | $12.8^a$ |

* Within each equilibrium moisture content (EMC) category, values designated by the same alphabetical letters are not significantly different.

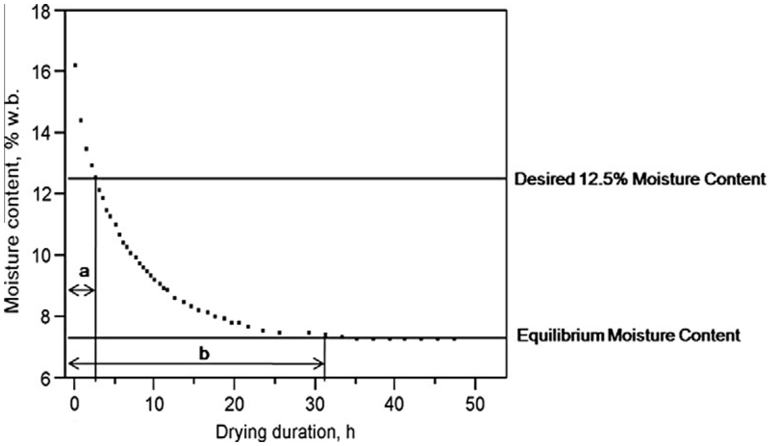

**Fig. 4.** Schematic of the procedure used to determine the drying durations required to reach the desired 12.5% (a) and equilibrium (b) moisture contents.

**Table 3**
Drying durations (in hours) required to reach 12.5% moisture content (wet-basis) for Wells and Jupiter rice samples initially at 19.6% and 17.8% moisture content, respectively, and dried at 26–34 °C and 19–47% relative humidity (RH). Each experimental value is an average of four duplicates.

| Temperature (°C) | RH (%) | Drying duration (h) | |
|---|---|---|---|
| | | Wells | Jupiter |
| 26 | 19 | 12.1 | 10.3 |
| 26 | 42 | 23.8 | 17.1 |
| 30 | 21 | 7.4 | 6.5 |
| 30 | 45 | 14.6 | 12.9 |
| 34 | 23 | 5.7 | 4.5 |
| 34 | 47 | 10 | 8 |

**Table 4**
Head-rice yields (HRYs) of rice samples dried at 26–34 °C and 19–47% relative humidity (RH) to approximately 12.5% moisture content (wet-basis). Each experimental value is an average of four duplicates.

| Cultivar | Temperature (°C) | RH (%) | HRY (%) |
|---|---|---|---|
| Wells | 26 | 19 | 61.0 |
| | | 42 | 61.4 |
| | 30 | 21 | 60.1 |
| | | 45 | 60.6 |
| | 34 | 23 | 60.8 |
| | | 47 | 61.5 |
| | Control | | 60.1 |
| Jupiter | 26 | 19 | 53.8 |
| | | 42 | 53.5 |
| | 30 | 21 | 53.9 |
| | | 45 | 53.6 |
| | 34 | 23 | 53.9 |
| | | 47 | 53.0 |
| | Control | | 52.1 |

### 3.5. Color

Rice whiteness, expressed as $L^*$ values (from the $L^*$, $a^*$, $b^*$ scale), of Wells and Jupiter head-rice samples were not significantly different from those of controls (Table. 5). Similar results were obtained by Sugunya et al. (2004) who showed that sun drying and other drying methods using modified air at low-temperatures (<40 °C) resulted in the greatest degree of rice whiteness. Bunyawanichakul et al. (2005) found that rice whiteness decreased with increasing grain drying temperatures and drying durations. Yellowing of rice has been shown to increase with increasing exposure to high temperatures (>45 °C) due to chemical and physical transformations induced by heating (Dillahunty et al., 2001), and translocation of color from the rice husk and bran to the endosperm (Inprasit and Noomhorm, 2001).

**Table 5**
Color, measured on the $L^*$, $a^*$, $b^*$ scale, of Wells and Jupiter rice samples dried at 26–34 °C and 19–47% relative humidity (RH) to approximately 12.5% moisture content (wet-basis). Each experimental value is an average of four duplicates.

| Cultivar | Temperature (°C) | RH (%) | $L^*$ | $a^*$ | $b^*$ |
|---|---|---|---|---|---|
| Wells | 26 | 19 | 75.2 | −1.30 | 15.4 |
| | | 42 | 76.0 | −1.45 | 15.5 |
| | 30 | 21 | 71.4 | −1.14 | 17.2 |
| | | 45 | 75.1 | −1.40 | 15.5 |
| | 34 | 23 | 73.3 | −0.37 | 15.6 |
| | | 47 | 75.2 | −0.90 | 14.9 |
| | Control | | 75.6 | −1.00 | 14.4 |
| Jupiter | 26 | 19 | 68.5 | −0.31 | 16.7 |
| | | 42 | 69.7 | −0.50 | 16.5 |
| | 30 | 21 | 65.6 | 0.14 | 17.4 |
| | | 45 | 68.7 | −0.34 | 15.9 |
| | 34 | 23 | 65.6 | 0.07 | 17.0 |
| | | 47 | 68.4 | −0.41 | 16.0 |
| | Control | | 69.5 | −0.51 | 16.6 |

**Table 6**
Peak and final viscosities (expressed in RVA units) of Wells and Jupiter rice samples dried at 26–34 °C and 19–47% relative humidity (RH) to the desired 12.5% moisture content (wet-basis). Each experimental value is an average of four duplicates. For each rice cultivar and parameter (peak or final viscosity) values designated by the same alphabetical letter are not significantly different.

| Cultivar | Temperature (°C) | RH (%) | Peak viscosity | Final viscosity |
|---|---|---|---|---|
| Wells | 26 | 19 | $325^{a}$ | $269^{a}$ |
| | | 42 | $331^{b}$ | $272^{a}$ |
| | 30 | 21 | $322^{a}$ | $265^{a}$ |
| | | 45 | $332^{b}$ | $258^{a}$ |
| | 34 | 23 | $311^{a}$ | $265^{a}$ |
| | | 47 | $335^{b}$ | $285^{b}$ |
| | Control | | $322^{a}$ | $269^{a}$ |
| Jupiter | 26 | 19 | $308^{a}$ | $248^{a}$ |
| | | 42 | $302^{a}$ | $265^{b}$ |
| | 30 | 21 | $321^{b}$ | $264^{b}$ |
| | | 45 | $315^{b}$ | $238^{a}$ |
| | 34 | 23 | $302^{a}$ | $265^{b}$ |
| | | 47 | $325^{b}$ | $276^{b}$ |
| | Control | | $305^{a}$ | $238^{a}$ |

### 3.6. Pasting properties

The peak and final viscosities of rice flour from Wells and Jupiter head-rice samples are shown in Table 6. The test samples had greater peak and final viscosities compared to controls but the difference was not statistically significant for all conditions. Greater peak and final viscosities are indications of greater values of kernel hardness, which is highly correlated with better cooking quality (Ferrell and Pence, 1964; Borompichaichartkul et al., 2007; Daniels et al., 1998). As kernel hardness increases, water absorption and volume expansion increases while stickiness decreases (Ferrell and Pence, 1964; Wiset et al., 2005; Inprasit and Noomhorm, 2001).

## 4. Conclusion

This work has shown the potential of using air at low-temperatures and low RHs to dry rough rice without adversely affecting product quality. Experimental data describing thin-layer drying characteristics of rough rice were obtained under controlled conditions representing low-temperatures and low-relative humidities. The drying data was well described using the Page equation and equations were developed to predict drying parameters $k$ and $n$ as functions of temperature and RH within the range of the experimental conditions. Results showed that drying duration can be shortened significantly by reducing the RH at given temperature, particularly lower temperatures, thereby supporting the concept of dehumidification of drying air. Product quality, expressed as HRY and color of rice samples dried at low-temperatures and low RHs, was maintained. The peak and final viscosities of the low-temperature dried samples were same as controls.

## References

AACC, 1996. Approved Method of the AACC. Method 61-02 for RVA, ninth ed. American Association of Cereal Chemists, St. Paul, MN.

Abud-Archila, M., Courtois, F., Bonazzi, C., Bimbenet, J.J., 2000. A compartmental model of thin-layer drying kinetics of rough rice. Drying Technology 18 (7), 1389–1414.

Akal, D., Kahveci, K., Cihan, A., 2007. Mathematical modeling of drying of rough rice in stacks. Food Science Technology International 13 (6), 437–445.

ASABE, 2007. ASAE D245.6: 2007. Moisture Relationships of Plant-based Agricultural Products. ASAE Standards, 43rd ed. American Society of Agricultural and Biological Engineers, St. Josephs, MI, USA.

Ban, T., 1971. Rice cracking in high rate drying. Japanese Agricultural Research Quarterly 6, 113–116.

Basunia, M.A., Abe, T., 1998. Thin-layer drying characteristics of rough rice at low and high temperatures. Drying Technology 16 (3–5), 579–595.

Basunia, M.A., Abe, T., 2001. Thin layer solar drying characteristics of rough rice under natural convection. Journal of Food Engineering 47, 295–301.

Bonazzi, C., De Peuty, M.A., Themelin, A., 1997. Influence of drying conditions on the processing quality of rough rice. Drying Technology 15 (3–4), 1141–1157.

Borompichaichartkul, C., Wiset, L., Tulayatun, V., Tuntratean, S., Thetsupamorn, T., Impaprasert, R., Waedalor, I., 2007. Comparative study of effects of drying methods and storage conditions on aroma and quality attributes of Thai jasmine rice. Drying Technology 25 (7), 1185–1192.

Bradburn, N., Blunden, G., Cocker, R.D., Jewers, K., 1993. Aflatoxin contamination of maize. Tropical Science 33 (1), 418–428.

Bunyawanichakul, P., Walker, E.J., Sargison, J.E., Doe, P.E., 2005. Modeling and simulation of paddy grain (rice) drying in a simple pneumatic dryer. Biosystems Engineering 96 (3), 335–344.

Calderwood, D.L., 1975. Rough rice (paddy) drying methods in the United States. Tropical Stored Products Information 30 (1), 13–22.

Chen, C.C., Morey, R.V., 1989. Comparison of four EMC/ERH equations. Transaction of the ASAEI 32 (30), 983–990.

Chirife, J., Iglesias, H.A., 1978. Equations for fitting water sorption isotherms of foods. Part I – a review. Journal of Food Technology 13, 159–174.

Cihan, A., 1991. An Experimental Investigation of Rough Rice Drying. Unpublished Doctoral Dissertation. Yildiz Technical University, Istanbul.

Cihan, A., Ece, M.C., 2001. Liquid diffusion model for intermittent drying of rough rice. Journal of Food Engineering 49, 327–331.

Cihan, A., Kahveci, K., Hacihafizoglu, O., 2007a. Modeling of intermittent drying of thin layer rough rice. Journal of Food Engineering 79, 293–298.

Cihan, A., Kahveci, K., Hacihafizoglu, O., 2007b. A diffusion based model for intermittent drying of rough rice. Heat Mass Transfer 44, 905–911.

Cnossen, A.G., Jiménez, M.J., Siebenmorgen, T.J., 2003. Rice fissuring response to high drying and tempering temperatures. Journal of Food Engineering 59 (1), 61–69.

Daniels, M.J., Marks, B.P., Siebenmorgen, T.J., McNew, R.W., Meullenet, J.F., 1998. Effect of long grain rice storage history on end use quality. Journal of Food Science 63 (1), 832–835.

Dillahunty, A.L., Siebenmorgen, T.J., Buescher, R.W., Smith, D.E., Mauromoustakos, A., 2000. Effect of moisture content and temperature on respiration rate of rice. Cereal Chemistry 77 (5), 541–543.

Dillahunty, A.L., Siebenmorgen, T.J., Buescher, R.W., Smith, D.E., Mauromoustakos, A., 2001. Effect of temperature, exposure duration, and moisture content on color and viscosity of rice. Cereal Chemistry 78 (5), 559–563.

Dung, N.V., Bowrey, R.G., Fowler, R.T., 1980. Variables affecting the drying rate of paddy rice. Food Technology in Australia 32 (12), 604–606.

Ece, M.C., Cihan, A., 1993. A liquid diffusion model for drying rough rice. Transactions of the ASAE 36, 837–840.

Evanson, R.E., Herdt, R.W., Hossain, M. (Eds.), 1996. Rice Research in Asia: Progress and Priorities. International Research Institute-CAB International, Wallingford, UK, 418p.

Ferrell, R.E., Pence, J.W., 1964. Use of the amylograph to determine extent of cooking in steamed rice. Cereal Chemistry 41 (1), 1–9.

Hogan, J.T., Karon, M.L., 1955. Hygroscopic equilibria of rough rice at elevated temperatures. Agricultural and Food Chemistry 3 (10), 855–859.

Iguaz, A., Versada, P., 2007. Moisture desorption isotherm of rough rice at high temperatures. Journal of Food Engineering 79, 794–802.

Iguaz, A., Martin, M.B., Mate, J.I., Fernandez, T., Virseda, P., 2002. Modeling of effective moisture diffusivity of rough rice (Lido Cultivar) at low drying temperatures. Journal of Food Engineering 59 (2–3), 253–258.

Inprasit, C., Noomhorm, A., 2001. Effect of drying air temperature and grain temperature of different types of dryer operation on rice quality. Drying Technology 19 (1), 389–404.

Jayas, S.D., Cenkowski, S., Pabis, S., Muir, D.E., 1991. Review of thin-layer drying and wetting equations. Drying Technology 9 (3), 551–588.

Jindal, V.K., Siebenmorgen, T.J., 1987. Effects of oven drying temperature and drying time on rough rice moisture content determination. Transaction of ASAE 30 (1), 1185–1192.

Kahveci, K., Cihan, A., Ece, M.C., 2002. Liquid diffusion model for drying a stack of rough rice. International Journal of Energy Research 27, 1131–1143.

Kunze, O.R., Calderwood, D.I., 1985. Rough rice drying. In: Rice Chemistry and Technology. American Association of Cereal Chemists, Inc..

Kunze, O.R., Choudhury, M.S.U., 1972. Moisture adsorption related to the tensile strength of rice. Cereal Chemistry 49 (1), 684–696.

Meullenet, J.F., Bradley, C., Griffin, P.M., Daniels, M.J., 1999. Effects of rough rice drying and storage conditions on sensory profiles of cooked rice. Cereal Chemistry 76 (4), 483–486.

Nguyen, C.N., Kunze, O.R., 1984. Fissures related to post-drying treatments in rough rice. Cereal Chemistry 61 (1), 63–68.

Page, G., 1949. Factors Influencing the Maximum Rates of Air Drying Shelled Corn in Thin Layers. Unpublished Masters Thesis, Purdue University, Lafayette, IN.

Pearce, M.D., Marks, B.P., Meullenet, J.F., 2001. Effects of postharvest parameters on functional changes during rough rice storage. Cereal Chemistry 78 (4), 354–357.

Ranalli, R.P., Howell Jr., T.A., Siebenmorgen, T.J., 2003. Effects of controlled ambient aeration on rice quality during on-farm storage. Cereal Chemistry 80 (1), 9–12.

Sharma, A.R., Kunze, O.R., 1982. Post-drying fissure developments in rough rice. Transactions of the ASAE 25 (1), 465–468, 474.

Siebenmorgen, T.J., Yang, W., Sun, Z., 2004. Glass transition temperature of rice kernel determined by dynamic mechanical thermal analysis. Transactions of the ASAE 47 (3), 835–839.

Sugunya, W., Kanchana, D., Sakda, J., Boonmee, S., 2004. Effect of drying methods and storage time on the aroma and milling quality of rice (*Oryza sativa* L.) cv. Kao Dawk Mali 105. Food Chemistry 87 (3), 407–414.

Sun, Da-Wen, Byrne, C., 1998. Selection of EMC/ERH isotherm for rapeseeds. Journal of Agricultural Engineering Research 69, 307–315.

Sun, Da-Wen, Woods, J.L., 1994. Low temperature moisture transfer characteristics of barley thin layer models and equilibrium isotherms. Journal of Agricultural Engineering Research 59, 273–283.

Wiset, L., Srzednicki, G., Wootton, M., Driscoll, R.H., Blakeney, A.B., 2005. Effects of high-temperature drying on physicochemical properties of various cultivars of rice. Drying Technology 23 (9–11), 2227–2237.

Zhou, Z., Robards, K., Helliwell, S., Blanchard, C., 2003. Effect of rice storage on pasting properties of rice flour. Food Research International 36 (1), 625–634.