THE GLASS TRANSITION TEMPERATURE CONCEPT IN RICE DRYING AND TEMPERING: EFFECT ON DRYING RATE

A. G. Cnossen, T. J. Siebenmorgen, W. Yang

ABSTRACT. *Research on rice drying and tempering has shown that high drying temperatures (up to 60° C) and high moisture removal rates (up to 6 percentage points moisture content) can be used without reducing milling quality as long as sufficient tempering at a temperature above the glass transition temperature (T_g) is allowed between drying passes. Using drying air temperatures above the T_g of the rice significantly reduces drying and tempering durations since kernel moisture diffusivity is much higher above T_g. Understanding the effects of glass transition is important in optimizing the drying and tempering processes in terms of overall required drying durations to achieve given moisture removals. The objective of this study was to investigate the effect of T_g on drying rates when using drying air temperatures above and below T_g. Both medium–grain and long–grain rice was harvested during 2000 and dried under various air conditions above and below the T_g of the rice. Results showed that rice dried significantly faster above T_g than below T_g. In addition, high temperature/low relative humidity drying air conditions, which result in a low equilibrium moisture content, apparently caused the surface of the kernel to transition from a rubbery to a glassy state and reduced the drying rate.*

Keywords. *Rice, Drying rate, Glass transition temperature.*

Rice is harvested at a moisture content (MC) too high to be safely stored, and it must therefore be dried. Typical harvest MCs range from 16% to 20%, while the safe storage MC is 12% (unless otherwise specified, all moisture contents are expressed on a wet basis). Drying causes stress inside the rice kernel, especially high drying air temperatures, which may result in kernel fissuring and subsequent breakage. In commercial rice drying, the MC is reduced in several drying passes; about 2 to 4 percentage points of MC are removed per pass. A tempering period is used in between each pass to allow MC gradient relaxation in the rice kernel, which helps prevent kernel fissuring. Rice drying and tempering has been studied extensively (Chen, 1997; Chen et al., 1997; Cnossen and Siebenmorgen, 2000; Cnossen et al., 1999; Kunze, 1979; Mossman, 1986; Steffe and Singh, 1980b) with the goal of drying rice more quickly while minimizing fissuring levels and thus maintaining high milling yields.

GLASS TRANSITION EFFECTS

Understanding kernel drying and tempering requires an integration of engineering principles, such as heat and mass transfer theory, and cereal science principles dealing with material properties (Siebenmorgen, 1998). Recent research (Cnossen and Siebenmorgen, 2000; Perdon et al., 2000) has shown that material properties of rice kernels, which are affected by MC and temperature, play an important role in rice drying. This drying and tempering research has attempted to directly integrate material properties at specific temperatures and MCs into drying theory. The glass transition temperature (T_g) concept (Cnossen and Siebenmorgen, 2000; Cnossen et al., 1999; Jiménez et al., 2002; Perdon et al., 2000) has been used to explain trends in drying rate and fissure formation.

Perdon et al. (2000) concluded that the change of state of starch, as it goes through a glass transition, plays an important role in rice drying and tempering in terms of kernel fissuring potential. Glass transition temperatures measured by Perdon et al. (2000) are within the temperature range typically encountered during rice drying (35° C to 50° C). Starch, the main constituent of rice, undergoes a glass transition as the kernel temperature increases above the T_g (Slade and Levine, 1991, 1995; White and Cakebread, 1966). At a temperature below the T_g, starch exists as a “glassy” material, with low expansion coefficients, specific volume, and diffusivity. As the kernel temperature increases above the T_g, the starch transitions from a glassy to a rubbery state with higher expansion coefficients, specific volume, and diffusivity. Figure 1 shows a T_g relationship (also called a state diagram) for medium–grain rice variety Bengal as measured by Sun et al. (2002), indicating that the T_g is inversely related to MC (i.e., as MC increases, T_g decreases). Perdon et al. (2000) showed a similar state diagram for long–grain variety Cypress rice.

The changes in volumetric expansion and specific volume during a glass transition will have an effect on kernel fissuring, discussed in detail by Cnossen and Siebenmorgen (2000), while the changes in diffusivity will greatly affect the

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The authors are **Auke G. Cnossen**, Research Specialist; **Terry J. Siebenmorgen**, **ASAE Member Engineer**, Professor; and **Wade Yang**, **ASAE Member Engineer**, Research Assistant Professor; Department of Food Science, University of Arkansas, Fayetteville, Arkansas. **Corresponding author**: Terry J. Siebenmorgen, Department of Food Science, University of Arkansas, 2650 N. Young Avenue, Fayetteville, AR 72704; phone: 501–575–2841; fax: 501–575–6936; e–mail: tsiebenm@uark.edu.

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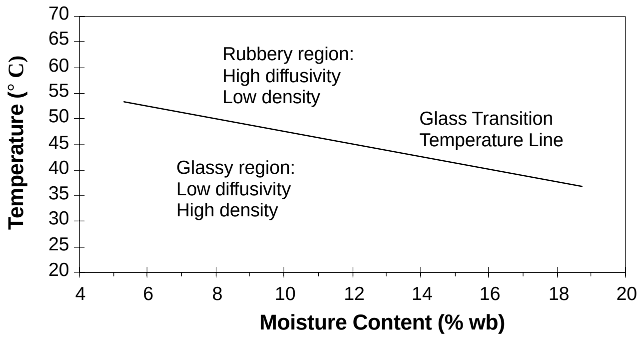

Figure 1. Glass transition relationship for Bengal brown rice (Sun et al., 2002).

drying and tempering rates. Understanding these changes is critical to understanding and improving the drying process.

The Rice Drying Process

Many drying equations have been developed to quantify the drying process of grains. The ASAE standards lists the thin layer drying equation (*ASAE Standards*, 1999):

$$MR = \frac{MC - EMC}{IMC - EMC} = \exp(-kt) \quad (1)$$

where

MR = moisture ratio of the grain at drying duration t (min)

MC = moisture content of the grain (decimal dry basis, d.b.)

EMC = equilibrium moisture content (decimal d.b.) of the grain corresponding to the drying air

IMC = initial moisture content (decimal d.b.)

k = drying rate constant (min^{-1}). The drying rate constant is an important parameter that reflects the rate at which water is removed from the kernel.

Previous work in thin layer drying has focused on quantifying the changes in the drying rate as a function of drying air conditions (Chen et al., 1997; Kunze, 1979). Researchers, Aguerre et al. (1982) and Yang et al. (2000) for rice and Becker and Sallans (1955) for wheat, showed that the temperature of the entire kernel increases rapidly (within 2 to 3 min) to the temperature of the drying air when drying in a thin layer fashion. In addition, it is generally agreed that temperature variations in the kernel can be neglected after the first few minutes of drying, and therefore, the kernel can be considered to be isothermal during drying (Aguerre et al., 1982; Ece and Cihan, 1993; Steffe and Singh, 1980a).

While the temperature of the kernel increases, the outer layers of the kernel lose moisture, resulting in the development of an MC gradient from the kernel center to the surface. When modeling the rice drying process, it is generally assumed (Ece and Cihan, 1993; Lu and Siebenmorgen, 1992; Steffe and Singh, 1980a) that the surface of the kernel will reach the equilibrium moisture content (EMC) associated with the drying air instantaneously at the onset of the drying process. The EMC of the rice resulting from exposure of the rice to a specific drying air condition (temperature and relative humidity) will be referred to as the EMC of the rice corresponding to the drying air in the rest of this article.

An MC gradient inside a rice kernel will result in a situation in which the different layers of the kernel could be characterized by different magnitudes of material properties (Cnossen and Siebenmorgen, 2000). If conditions are such that part of the kernel exists in one state while the rest of the kernel is in another state, then drastic property differences can exist that would affect the drying/fissuring process. Differential stresses resulting from the different magnitudes of material properties may cause kernel fissuring (Cnossen and Siebenmorgen, 2000), while differences in diffusivity will have an effect on drying rate.

With the knowledge of a state transition, the question arises as to how the state transition affects the drying rate. In particular, would drying at higher temperatures and higher relative humidities (RHs), with corresponding EMCs in the rubbery region, provide higher drying rates? The premise of this question is that moisture diffusivity is much higher when material temperatures are above T_g. With the higher diffusivity above the T_g, the kernel would be expected to dry faster. If drying conditions that would result in extremely low EMCs (achieved when using high temperatures and low RHs) are used, then the surface of the kernel dries quickly but also equilibrates with the drying air, and as a result, the kernel surface layer could transition back to the glassy state. This situation is illustrated in figure 2. Under this scenario, the lower diffusivity of the surface in the glassy state would limit diffusion from the rubbery center; the kernel would thus dry more slowly than if the surface were maintained above T_g.

Moisture Diffusivity

Many researchers (Achanta et al., 1995; Ece and Cihan, 1993; Lu and Siebenmorgen, 1992; Steffe and Singh, 1980a) have investigated the moisture diffusivity of grains and other food materials. Moisture diffusivity is known to increase with temperature. Brooker et al. (1974) stated that the relationship between diffusion coefficient (and thus also the drying rate constant k) and the grain temperature is usually of the so–called Arrhenius type:

$$D = C_1 \exp\left(\frac{-C_2}{T_{abs}}\right) \quad (2)$$

where

D = diffusion coefficient

C_1 and C_2 = constants depending on the particular grain

T_{abs} = absolute temperature.

Ece and Cihan (1993) developed a liquid diffusion model for drying rough rice. Only temperature and air velocity were

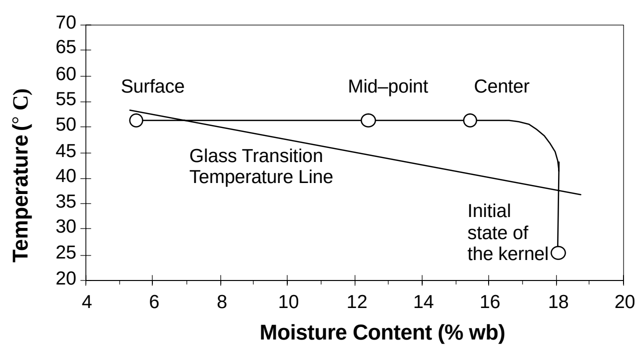

Figure 2. Hypothetical moisture content gradient inside a rice kernel after extended drying plotted onto a state diagram for brown rice. Surface, mid–point, and center refer to the surface, the mid–point between the surface and the center, and the center of the brown rice kernel, respectively.

taken into account; no reference was made to RH of the drying air. Steffe and Singh (1980a) determined the diffusivity of the various rough rice components.

Achanta et al. (1995) studied the transport of moisture in shrinking food gels during drying. They developed a drying theory proposing a structural transition from the rubbery to the glassy state in the material during drying. This would result in surface dry–out and skin/shell formation, which results in drying shut–off. This would occur if a high MC material, which is above T_g, was subjected to rapid drying conditions (high temperatures and low RHs).

It is generally known that the drying rate constant *k* is related to drying air temperature; as drying air temperature increases, the drying rate constant increases (Allen, 1960; Chen, 1997; Henderson and Pabis, 1961). Although drying air temperature (Ece and Cihan, 1993; Henderson and Pabis, 1961; Lu and Siebenmorgen, 1992; Steffe and Singh, 1980a) and kernel MC (Jaros et al., 1992) have been taken into account when calculating moisture diffusivity and drying rate constants for grains, no research on the effect of T_g on drying rates was found.

The drying air conditions that would be expected to cause a state transition (high temperature and low RH) are attainable in typical rice drying operations, as shown by Cnossen and Siebenmorgen (2000). They showed that drying air conditions that result in a low EMC (high temperature and low RH) in combination with high moisture removal rates, resulting in large MC gradients, could be used without reducing milling quality as long as sufficient tempering at a high temperature (above T_g) was allowed before cooling. In that study, both medium– and long–grain rice was dried with drying air conditions corresponding to EMCs of 5.8% (60°C, 16.9% RH) and 10.2% (60°C, 50% RH) and tempered for various durations at the drying temperature. Under these conditions, as much as 6 percentage points MC were removed without reducing milling yields if a tempering duration of 3 h at 60°C was used before cooling.

Understanding the effects of drying air temperature, specifically around the T_g, and RH on the drying rate of rough rice could help optimize the drying process. The objective of this study was to investigate the effect of T_g on rice drying rates, especially when using drying air conditions that result in low EMCs.

Materials and Methods

Rice varieties Bengal (medium–grain) and Cypress (long–grain) were harvested in 2000 from University of Arkansas Rice Research and Extension Centers at Stuttgart and Keiser, Arkansas, at 17.2% and 20.5% MC, respectively. For Cypress, the experimental design for the drying experiments consisted of 25 different drying air conditions resulting from the combination of drying air temperatures of 40°C, 45°C, 50°C, 55°C, and 60°C with various RHs corresponding to EMCs of 5.8%, 6.7%, 7.6%, 8.5%, and 9.4%, as predicted by the Chung equation (*ASAE Standards*, 1999) for rice (provisions for variations in EMC due to variety are not made in the Chung equation). To reduce the number of samples, only the 45°C, 50°C, and 55°C drying air temperatures were initially considered for Bengal. After analyzing the results, this design was expanded to include the 60°C drying air temperature. Table 1 gives an overview of the relative humidity setpoints for each drying air condition.

Table 1. Target relative humidity for each drying air temperature/EMC combination.

Temperature (°C)	EMC[a] (%)				
	5.8	6.7	7.6	8.5	9.4
40	12.8	19.2	26.9	35.2	43.8
45	14.5	21.3	29.2	37.6	46.1
50	16.2	23.3	31.3	39.8	48.3
55	17.9	25.2	33.4	41.9	50.2
60	19.6	27.1	35.4	44.8	52.1

[a] EMC is the equilibrium moisture content (wet basis) associated with the given drying air conditions as calculated with the Chung equation (*ASAE Standards*, 1999).

Thin layer (3 to 5 mm) drying of 50 g samples was achieved by using perforated trays, allowing the air to flow through the grain, in drying chambers in which the drying air conditions were controlled by a temperature and RH controller (Parameter Generation and Control, Inc., Black Mountain, N.C.). Three drying replications were performed for each drying air condition. Samples were removed from the drier after drying for 5, 10, 20, 40, 60, or 120 min. These samples were stored for 24 h at 21°C in sealed plastic ziplock bags to minimize moisture transfer. MC was determined the following day by drying duplicate 15 g samples for 24 h in an oven set at 130°C (Jindal and Siebenmorgen, 1987).

Due to the differences in the drying kinetics of rice dried above or below the T_g and the effect of the hypothesized transition of the kernel surface when drying above the T_g, Page's equation (eq. 3) would better fit the data than equation 1:

$$MR = \frac{MC - EMC}{IMC - EMC} = \exp(-kt^n) \tag{3}$$

where *n* is a dimensionless constant. In preliminary experiments, it was found that equation 3 indeed does give a better fit than equation 1. Therefore, equation 3 was used for calculating the drying rate constants.

Regression was performed with the commercial curve–fitting software Table Curve 2D (Jandal Scientific, Corte Madera, Cal.) to fit equation 3 to the MC data to determine the drying rate constant *k*, the constant *n*, the standard error (SE), and R^2 for each drying air condition. In order to compare the *k* values among drying air conditions without the *k* values being affected by the variation of the constant *n*, a fixed value for *n* was used for each drying air temperature. This *n* value was determined by first fitting equation 3 to the MC data for each of the 25 temperature/RH air conditions tested. Subsequently, an average *n* was calculated for each set of temperature/RH air conditions at a given air temperature; thus, an average *n* was determined for each of the five temperature levels.

Equation 3 was then fitted to the MC data again using these average *n* values. For Cypress, the average *n* values were 0.506, 0.543, 0.606, 0.679, and 0.741, respectively, for the 40°C, 45°C, 50°C, 55°C, and 60°C drying air temperatures. For Bengal, the *n* values were 0.625, 0.635, 0.649, and 0.619, respectively, for the 45°C, 50°C, 55°C, and 60°C drying air temperatures. For all drying air temperatures, the difference in *n* between the drying air condition with the highest and lowest RH at a given drying air temperature was less than half of the difference between the average *n* value of that drying air temperature level and that of the next temperature level. Due to the different *n* values for each drying air temperature, the *k* values could not be compared between drying air temperatures. The R^2 values were higher than 0.98, indicating that the relationships explained much of the variability in the MR.

Statistical analyses, at a significance level of $\alpha = 0.05$, were performed using the software package JMP (SAS Institute, Inc., Cary, N.C.).

RESULTS AND DISCUSSION

During drying, the surface of the kernel reaches an MC equal to the EMC corresponding to the drying air conditions. The conditions at the surface of the brown rice kernel (temperature, MC, and resultant state of the starch) determine the drying rate. Plotting the EMCs corresponding to the drying air conditions onto a state diagram indicates whether the surface of the brown rice kernel was in the glassy state or in the rubbery state during most of the drying. Figure 3 shows the 25 drying air conditions with their corresponding EMCs plotted onto a state diagram for brown rice developed by Sun et al. (2002). As can be seen in figure 3, the surface of the kernel was in the rubbery region when drying at 55° C and 60° C and in the glassy region when drying at 40° C and 45° C. When drying at 50° C, the low RH air would drive the surface of the kernel into the glassy region, and therefore drying would be expected to be slower than when higher RHs would be used at this temperature.

The T_g line in figure 3 is a regression line with associated scatter in individual kernel T_g values; the temperature at which the glass transition occurs differs among individual kernels. Therefore, when bulk samples are dried with air conditions near the T_g line, some kernels may be in the rubbery region while others may be in the glassy region. The greater the number of kernels that are in the glassy region, the slower the overall drying process. In addition, the greater the number of kernels in the rubbery region of which the surface has transitioned back to the glassy region, the slower the drying process. The individual kernel MC distribution within a batch of rice may affect drying as well. Even though the average MC of a batch of rice falls within one region (rubbery or glassy), a number of kernels may exist in the other region.

DRYING RATES FOR CYPRESS RICE

Figure 4 shows the drying rate constant *k* versus the EMC corresponding to the drying air for all five drying air temperatures for Cypress. As can be seen in figure 4, the drying rate increases when the EMC decreases from 9.4% to 6.7% when drying at 60° C, 55° C, and 50° C. However, the drying air condition corresponding to 5.8% EMC showed a significantly lower drying rate constant compared to the drying air condition corresponding to 6.7% EMC for these three drying air temperatures. This sharp drop in drying rate constant may be the result of a transition of the kernel surface from the rubbery to the glassy region for a significant number of kernels at the drying air condition corresponding to 5.8% EMC. The lower diffusivity in the glassy region would have led to lower *k* values and slower drying rates, even though the drying air RH and corresponding EMC were lower.

When using a drying air temperature of 45° C or 40° C, drying occurred primarily in the glassy region for most kernels in the sample and was, therefore, slower than when

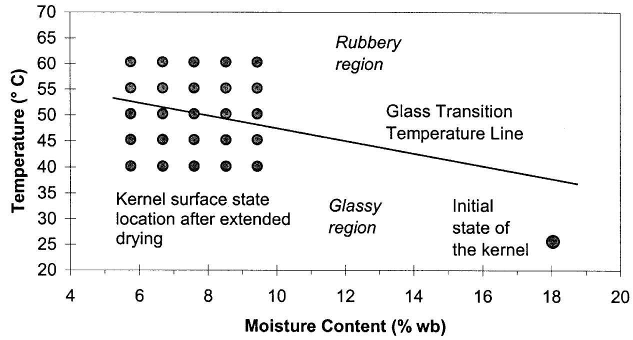

Figure 3. Kernel surface state location after extended drying for each equilibrium moisture content (5.8%, 6.7%, 7.6%, 8.5%, and 9.4%) and drying air temperature combination plotted onto a state diagram for brown rice, as measured by Sun et al. (2002).

drying above T_g in the rubbery region. When drying at 45° C, the RH of the drying air only had a small effect on the drying rate constant *k*; when drying at 40° C, the RH of the drying air did not have a significant effect on the drying rate constant *k*.

DRYING RATES FOR BENGAL RICE

As can be seen from figure 5, the effect of EMC corresponding to the drying air on the drying rate constant was less significant for Bengal than it was for Cypress. A significant difference in *k* value due to EMC was observed only at the 45° C drying air temperature; only the drying air condition corresponding to 9.4% EMC was significantly lower than the other drying air conditions at this temperature. For all other drying air temperatures, drying rate constants were not significantly different.

Due to the fact that Bengal is a shorter and thicker kernel compared to long–grain Cypress, which results in a lower surface area per unit weight of kernel and thus a lower convective mass transfer area, the diffusion of moisture from the kernel surface of Bengal is of lesser relative importance in determining the drying rate than with Cypress. Rather, the internal moisture movement becomes a more limiting factor with Bengal. This internal diffusion is much more affected by kernel temperature than by the moisture concentration on the surface of the kernel. In addition, differences in endosperm structure between Cypress and Bengal may affect the internal diffusion. Consequently, they cannot be compared here.

Figure 5 shows that at 60° C, 55° C, and 50° C, while not statistically different, the trend in drying rate constant shows a slight decrease with decreasing EMC below the 7% to 8% EMC level for Bengal. This could be due to the same effect speculated for Cypress (i.e., the surface of the kernel transitioning back to the glassy state) for the drying air conditions resulting in low EMC at high drying air temperatures.

PERCENTAGE POINTS OF MC REMOVED

Due to the fact that different *n* values were used for each drying air temperature, the *k* values cannot be compared across drying air temperatures. Therefore, an analysis is presented in which the amount of MC removed was calculated and used as a basis for comparison.

The amount of moisture removed after 20 min of drying, which resulted in 2 to 4 percentage points of MC removal, was compared across EMCs (table 2). As can be seen in

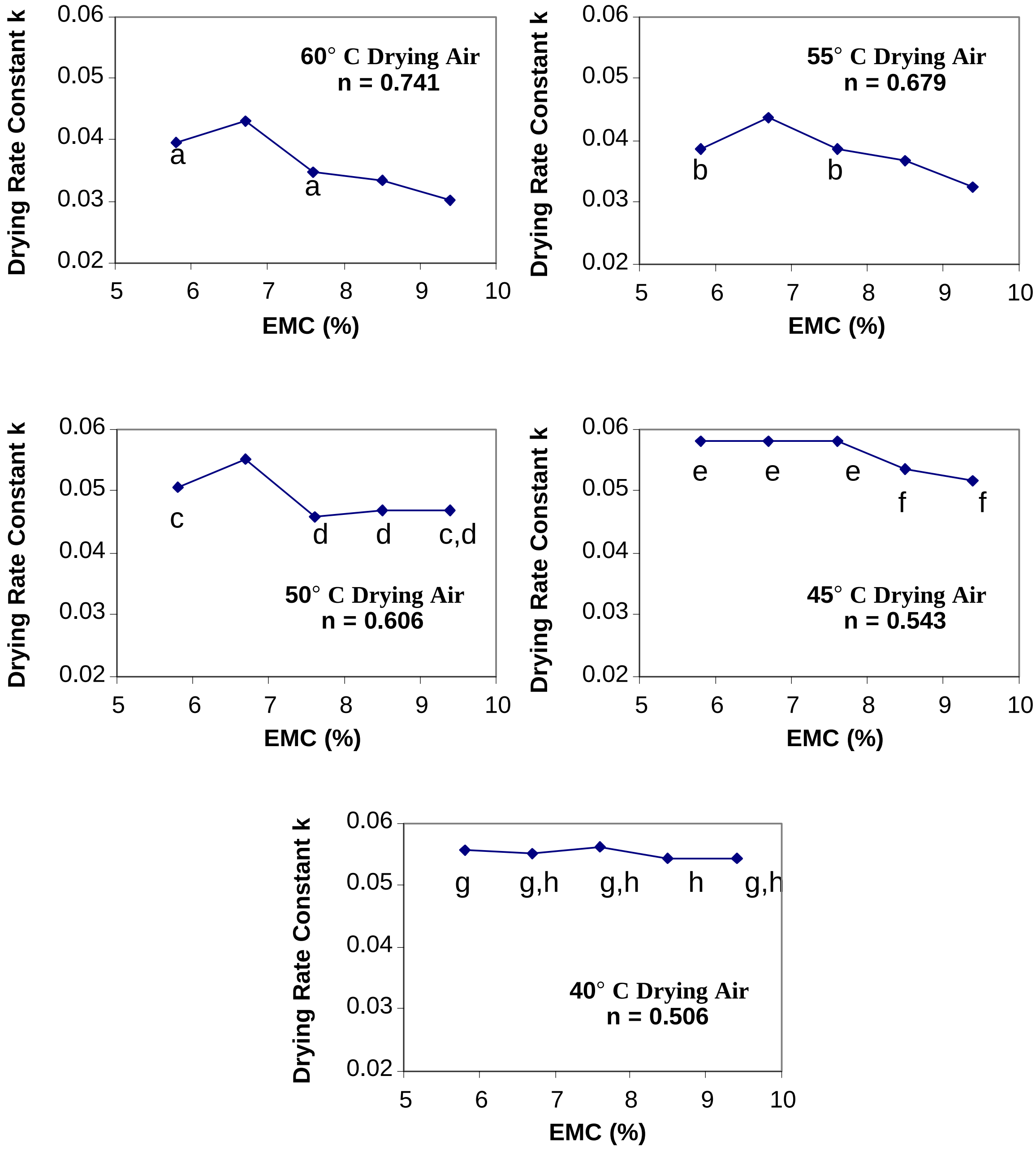

Figure 4. Drying rate constant *k* versus equilibrium moisture content (EMC) associated with the drying air for five different drying air temperatures for Cypress rice. The *n* values are the constants from the Page equation. The harvest MC was 20.5%. Values with the same letter are not significantly different (α = 0.05). All standard deviations were less than 0.0027.

table 2, the higher drying rate constants at the drying air condition corresponding to 6.7% EMC for the 60° C and 55° C drying air temperatures compared to the drying air condition corresponding to 5.8% EMC for Cypress did result in a higher amount of moisture being removed in the first 20 min of drying. The percentage points MC removed after 20 min (table 2) show the same trend as the drying rate constants in figure 4 for the 60° C, 55° C, and 50° C drying air temperatures (i.e., the amount of MC removed increased with decreasing EMC until a drying air condition with an EMC of 5.8% was used). This is believed to correspond to a rubbery to glassy transition. For the 45° C and 40° C drying air temperatures, the amount of moisture removed after 20 min of drying decreased with increasing EMC; a state transition is not believed to have occurred at these temperatures (fig. 3). From table 2 it can be seen that a state transition, even though it may have occurred, did not have an effect on the amount of MC removed for all drying air temperatures.

Table 3 shows the average amount of moisture removed after 120 min for each drying air condition for both Bengal and Cypress. As can be seen in table 3, the drying air temperature had a large effect on the amount of moisture that was removed after 120 min of drying. For Cypress, only the amount of moisture removed at the drying air condition corresponding to 8.5% EMC under the 55° C and 50° C drying air temperatures were not significantly different. All other values were significantly different across drying air temperatures.

The higher drying rate constants at the drying air condition corresponding to 6.7% EMC for the 60° C, 55° C, and 50° C

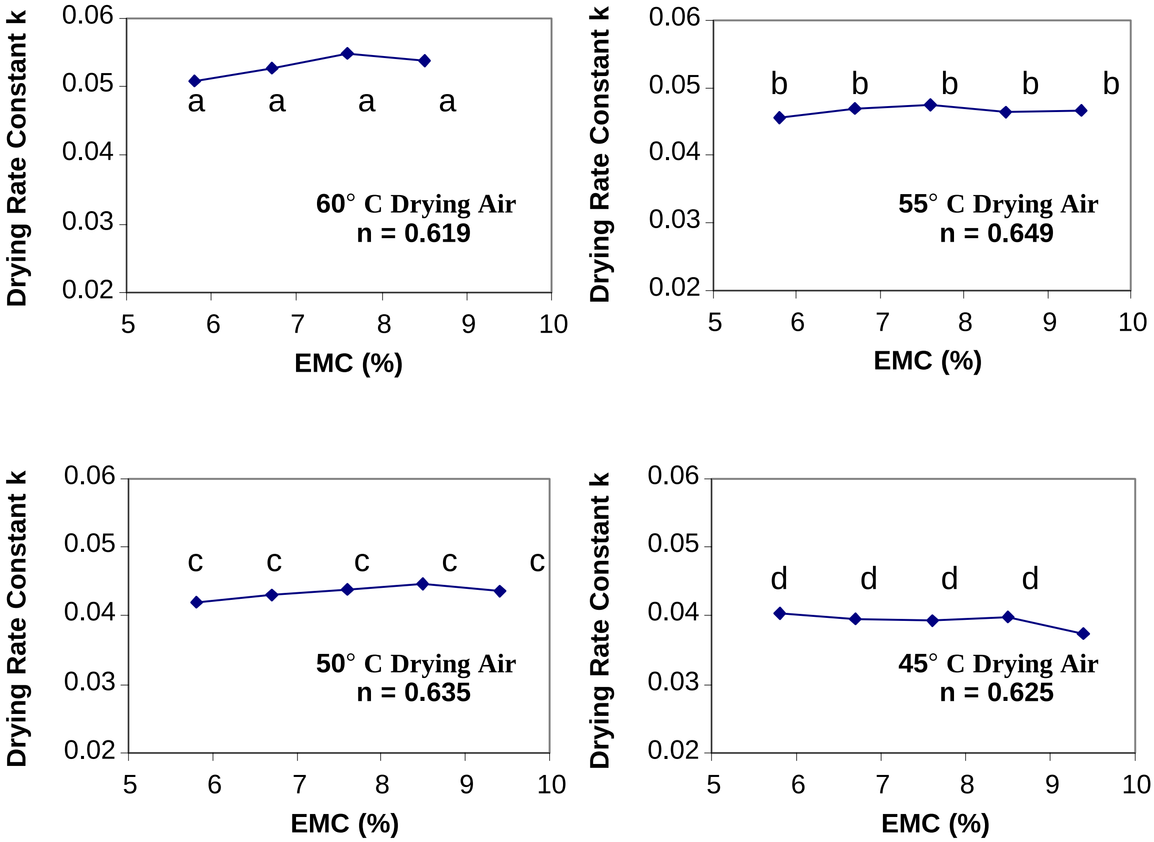

Figure 5. Drying rate constant *k* versus equilibrium moisture content (EMC) associated with the drying air for five different drying air temperatures for Bengal rice. The *n* values are the constants from the Page equation. The harvest MC was 17.2%. Values with the same letter are not significantly different (α = 0.05). All standard deviations were less than 0.0025.

Table 2. Average percentage points MC removed after 20 min of drying for each drying condition. Values are the average of three drying runs.

Drying Air Temperature (°C)	EMC Corresponding to the Drying Air Conditions (%)[a]				
	5.8	6.7	7.6	8.5	9.4
Cypress					
60	3.76 a	4.10	3.59 a	2.93	2.43
55	3.51	3.82	3.20	2.77	2.45
50	3.52 b	3.66 b	2.93	2.63 c	2.43 c
45	3.32	3.05	2.85	2.52	2.17
40	3.07 d	2.91 d	2.49	2.19 e	2.06 e
Bengal					
60	2.88 f	2.81 f	2.52 g	2.22 g	—[b]
55	2.81 h	2.59 h,i	2.34 i,j,k	1.97 j,k	1.84 k
50	2.61 l	2.39 l,m	2.19 m	1.96 m	1.54
45	2.47	2.26	1.95 n	1.82 n	1.51

[a] Values followed by the same letter are not significantly different (α = 0.05) across EMCs.
[b] No data.

Table 3. Average percentage points MC removed after 120 min of drying for each drying condition. Values are the average of three drying runs.

Drying Air Temperature (°C)	EMC Corresponding to the Drying Air Condition (%)[a][b]				
	5.8	6.7	7.6	8.5	9.4
Cypress					
60	9.48	9.06 a	8.75 a	8.07	7.39
55	8.80	8.61	7.94	7.24 K	6.87
50	7.97 b	7.92 b	7.10 c	6.99 c,K	6.38
45	7.27 d	7.05 d	6.60 e	6.59 e	5.53
40	6.49	6.05 f	5.96 f	5.32	4.93
Bengal					
60	7.31 g	7.36 g	7.06	6.58	—[b]
55	6.53 h	6.43 h	5.97	5.55	4.98
50	5.97	5.54	5.24 i	5.03 i	4.04 M
45	5.49	5.23	4.76	4.57	4.11 M

[a] Values followed by the same lowercase letter are not significantly different (α = 0.05) across EMCs.
[b] Values followed by the same capital letter are not significantly different (α = 0.05) across drying air temperatures.
[c] No data.

drying air temperatures compared to the drying air condition corresponding to 5.8% EMC for Cypress did not result in a higher amount of moisture being removed after 120 min of drying. The speculated transition of the kernel surface, as indicated by the trends in drying rate constants and the amount of moisture removed after 20 min, is not reflected in the moisture removed after 120 min of drying. This would suggest that the transition of the surface of the kernel back to the glassy state would only have an effect at the beginning of drying. As drying progresses, the internal moisture migration through diffusion, which is affected by the MC gradient inside the kernel, becomes the limiting factor that determines the drying rate. This is illustrated in figure 6, which shows the drying curves of the drying air conditions corresponding to the 5.8% and 6.7% EMC for the 60° C drying air temperature. As can be seen, at the beginning of drying the drying air condition corresponding to 6.7% EMC dries faster, but eventually the drying curve is dictated by the EMC

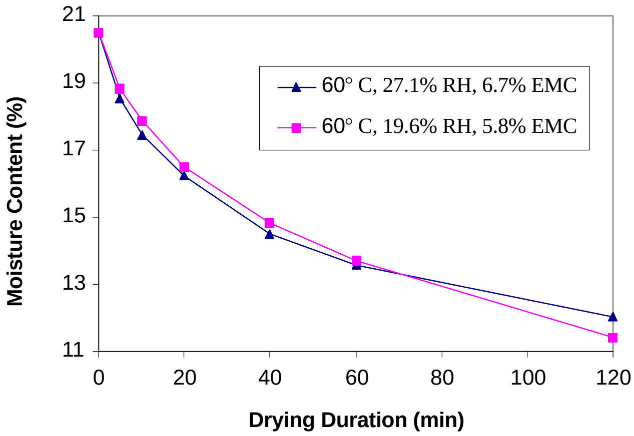

Figure 6. Moisture content versus drying duration for two drying air conditions. RH is the relative humidity of the drying air, and EMC is the equilibrium moisture content associated with the drying air condition. Points are the average of three drying runs.

corresponding to the drying air condition. In figure 6, the MC values after 10 min of drying and after 120 min of drying are significantly different between the two drying air conditions. The standard deviations at these points are in the range of 0.05 to 0.1.

The amount of moisture removed after 120 min for Bengal was much lower than for Cypress. This was due in part to the lower harvest MC (17.2%) for Bengal compared to Cypress (20.5%). Drying rates decreased with decreasing harvest MC. In addition, Bengal rice has a thicker kernel with relatively less surface area per unit weight, which resulted in a slower drying process.

In contrast to Cypress, no signs of a kernel surface state transition (from the rubbery back to the glassy state) for the drying air conditions resulting in low EMCs were found for Bengal after 20 min of drying (table 2). This concurred with the trends in drying rates, which suggest that the internal moisture movement is the limiting factor determining the drying rate. For Bengal, only the amount of moisture removed after 120 min at the drying air condition corresponding to 9.4% EMC was not significantly different between the 50°C and 45°C drying air temperatures (table 3). All other values were significantly different across drying air temperatures.

Conclusions

- Drying air temperatures above the T_g of the rice significantly increased the drying rate compared to those below the T_g for both varieties.
- The drying rate increased significantly with decreasing EMC (from 9.4% to 6.7%) corresponding to the drying air condition for the 60°C, 55°C, and 50°C drying air temperatures for Cypress rice. However, a further decrease in EMC resulted in a lower drying rate. When using low drying air conditions with corresponding low EMCs, the surface of the kernel is speculated to transition back from the rubbery to the glassy region with a resultant drop in diffusivity at the kernel surface. Therefore, drying would be slower than when a higher RH is used at this temperature and the surface is maintained in the rubbery region.
- Both the drying rate constants and the amount of moisture removed after 20 min of drying showed that the kernel surface state initially determines the drying rate constant. As drying progresses, the drying curve will eventually be dictated by the EMC corresponding to the drying air condition.
- EMC corresponding to the drying air condition did not have a significant effect on the drying rate constant k for medium–grain Bengal rice either above or below the T_g of the rice.

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