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Relationship of Kernel Moisture Content Gradients and Glass Transition Temperatures to Head Rice Yield

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The relationship of glass transition temperature T_g and moisture content (MC) gradient of rice kernels to head rice yield (HRY) variation was investigated. Mathematical models describing heat and moisture transfer inside rice kernels during drying were developed and solved using the finite element method. Moisture distributions inside a kernel were simulated and verified using thin-layer drying experiments, and the intra-kernel MC gradients during drying were accordingly determined and analysed. Results showed that in the glassy region, rice did not incur measurable HRY reduction after drying. However, when rice was dried in the rubbery region and then cooled down immediately without being tempered following drying, HRY decreased markedly after MC gradients exceeded certain levels. It was found in this study that the time when the percentage point of moisture removal reached a maximally allowable level before HRY decreased dramatically coincided with the time at which the curve of kernel MC gradients *versus* drying duration reached its peak. Such a relation was verified with the HRY data of two varieties (Cypress and M202) as measured in this study and cited from literature. The HRY trends for these two varieties were well explained through the behaviour of glass transition and MC gradients of rice.

1. Introduction

Head rice yield (HRY), the mass percentage of rough rice that remains as head rice after milling, is one of the most important quality characteristics of rice. Head rice is defined as milled kernels that are at least three-fourths of the original kernel length (USDA, 1990). Rice kernels with fissures (internal cracks) are more susceptible to breakage during subsequent hulling and milling, resulting in HRY reduction. HRY is especially sensitive to drying conditions and is commonly taken as an indicator to assess the effect of a rice drying system on rice quality. It has been a long-term objective of researchers to develop a rice drying process that can maximise the throughput at minimal HRY loss with efficient energy consumption (Brooker *et al.*, 1992). It has been reported that MC gradient was one of the main factors that caused a non-uniform contraction within a single kernel and resulted in fissure or crack formation (Thompson & Fortes, 1963; Rao *et al.*, 1975; Kunze, 1979; Litchfield & Okos, 1988; Sarker *et al.*, 1996; Jia *et al.*, 2000a; Yang *et al.*, 2002).

It is well known that the physical and thermal properties and the microstructures of grain kernels can change under different drying conditions. Zoerb (1958) concluded that moisture content had the greatest influence on the mechanical properties of grain. According to conclusions made by Ekstrom *et al.* (1966), the coefficient of thermal expansion and other physical properties were closely related to grain temperature variation; a distinct change in properties was observed to take place around 43°C. A similar phenomenon was also observed by Arora *et al.* (1973).

Misra *et al.* (1981) found that prediction of stresses based on the assumptions of elastic material was not adequate for soya beans, and a viscoelastic analysis of stress distribution in rice kernels was carried out by Lan *et al.* (2000). Perdon (1999) reported that the state of rice

Notation

A	total surface area of a triangular element, m^2	$\dot{M}$	$\partial\{M\}/\partial t$
c_g	specific heat of grain, $J\,kg^{-1}\,K^{-1}$	$\bar{M}$	mass average moisture content (d.b.)
c_v	specific heat of water vapour, $J\,kg^{-1}\,K^{-1}$	n	gradient normal to kernel surface
$[C]$	element capacitance matrix	Q_{fg}	latent heat of vaporisation, $J\,kg^{-1}$
D	diffusion coefficient, $m^2\,s^{-1}$	t	drying time, s
$\{F\}$	element force vector	T	temperature, °C
F_M	element force derived from the hygroscopic load, N	$\dot{T}$	$\partial\{T\}/\partial t$
F_T	element force derived from the thermal load, N	T_g	glass transition temperature, °C
h_m	convective mass transfer coefficient, $m\,s^{-1}$	V	volume of a single grain kernel, m^3
h_t	convective heat transfer coefficient, $W\,m^{-2}\,°C^{-1}$	ρ	density of a single grain kernel, $kg\,m^{-3}$
k	thermal conductivity of a single grain kernel, $W\,m^{-1}\,°C^{-1}$		
$[K]$	element conductance matrix	*Subscripts*	
m	mass of an element, kg	0	initial
M	moisture content inside a grain kernel (d.b.) (d.b. used in simulation and converted to w.b. at the end)	a	drying air
		e	equilibrium
		g	grain
		v	water vapour

endosperm experienced a transition from the glassy state to the rubbery state and vice versa during the commercial drying or cooling process, and the glass transition temperature T_g might have played an important role in rice drying. The work done by Chen *et al.* (1999) pointed to possible relationship between HRY and the glass transition inside a rice kernel.

An accurate description of the drying process depends to a large extent upon an accurate description of moisture distribution within a single kernel. The numerical solution of a diffusion equation can, when properly validated with thin-layer drying data, effectively determine the magnitude of MC gradients inside a single kernel during drying (Haghighi & Segerlind, 1988; Irudayaraj *et al.,* 1992; Jia *et al.*, 2000b; Yang *et al.*, 2002). Some work has been done to relate HRY to moisture adsorption or desorption process (Banaszek & Siebenmorgen, 1993; Chen *et al.*, 1997, 1999) and to relate T_g to the rice drying process (Perdon, 1999; Cnossen *et al.*, 1999; Cnossen & Siebenmorgen, 2000; Perdon *et al.*, 2000; Cnossen *et al.*, 2000b). Examination of the relation of T_g and maximal MC gradients to the measured HRY trend under various drying conditions is important for understanding the drying mechanism and fissure formation in rice kernels.

During the drying process, a rice kernel dries unevenly, with MC gradients left from the surface to the centre of the kernel (Sarka *et al.*, 1996; Chen *et al.*, 1999; Yang *et al.*, 2002). Because of the MC gradients, different parts inside a rice kernel would undergo a glass transition at a different drying duration. When the kernel is heated up to the temperature of drying medium (say, 60°C), it goes across the glass transition line from the glassy to the rubbery state in a state diagram. As drying progresses at the temperature of drying medium, MC gradients build up inside the kernel. The region close to the surface has lower MC and that near the centre has higher MC. This causes uneven glass transition zones inside the kernel, namely, some parts of the kernel (*e.g.*, the parts close to the surface) have already transitioned from the rubbery state back to the glassy state, while some other parts (*e.g.*, the parts near the centre) are still in the rubbery region, resulting a difference in expansion and/or contraction in different glass transition zones and consequently a possibility for fissure to form. The key to understand where inside the kernel glass transition may take place during the drying process is the MC gradients that can be obtained by numerical simulation technique.

Therefore, the objective of this study was to examine the relationship of intra-kernel MC gradients and glass transition temperatures to HRY trend for rough rice undergoing heated-air drying.

2. Materials and methods

2.1. *MC gradient determination by finite element method*

MC gradient determination in this study followed the same finite element procedure reported by Yang *et al.*

(2002), which is briefly summarised below. The governing equations describing the single-kernel drying process of rice in a cylindrical coordinate system are:

$$\frac{\partial M}{\partial t} = D\left(\frac{\partial^2 M}{\partial r^2}\right) + D\left(\frac{1}{r}\frac{\partial M}{\partial r}\right) + D\left(\frac{\partial^2 M}{\partial z^2}\right) \quad (1)$$

$$\rho_g c_g \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial r^2}\right) + k\left(\frac{1}{r}\frac{\partial T}{\partial r}\right) + k\left(\frac{\partial^2 T}{\partial z^2}\right) + \rho_g Q_{fg}\frac{1}{1+M}\frac{\partial M}{\partial t} \quad (2)$$

where: M is moisture content on a dry basis (d.b.); t is time in s; D is moisture diffusivity in $\mathrm{m^2\,s^{-1}}$; T is temperature in °C; ρ_g is density of the rice kernel in $\mathrm{kg\,m^{-3}}$; c_g is specific heat of the rice kernel in $\mathrm{kJ\,kg^{-1}\,K^{-1}}$; k is thermal conductivity of the rice kernel in $\mathrm{W\,m^{-1}K^{-1}}$; Q_{fg} is latent heat of vaporisation in $\mathrm{J\,kg^{-1}}$; and r and z are the cylindrical coordinates.

The corresponding boundary and initial conditions for Eqns (1) and (2) during drying are shown in Eqns (3) and (4).

$$-D\frac{\partial M}{\partial n} = h_m(M - M_e) \quad (3)$$

$$-k\frac{\partial T}{\partial n} = h_t(T - T_a) + \rho_g[Q_{fg} + c_V(T_a - T))]\frac{V}{A(1+M)}\frac{\partial M}{\partial t} \quad (4)$$

$$t = 0, \quad M = M_0, \quad T = T_0 \quad (5)$$

where: n is the gradient normal to kernel surface; h_m is convective mass transfer coefficient in $\mathrm{m\,s^{-1}}$; M_e is equilibrium moisture content on a d.b.; h_t is convective heat transfer coefficient in $\mathrm{W\,m^{-3}\,{}^\circ C^{-1}}$; T_a is the temperature of drying air in °C; c_v is specific heat of water vapour in $\mathrm{kJ\,kg^{-1}\,K^{-1}}$; V is volume of a single rice kernel in $\mathrm{m^3}$; and A is total surface area of a triangular element in $\mathrm{m^3}$.

The finite element modelling procedures used in this study were the same as in Yang *et al.* (2002). Green's formula was used to simplify the variation equations of the whole area of a triangular element. Equations (1) and (2) can therefore be expressed in a general matrix form:

$$[C]\begin{Bmatrix} \dot{M} \\ \dot{T} \end{Bmatrix} + [K]\begin{Bmatrix} M \\ T \end{Bmatrix} - \{F\} = 0 \quad (6)$$

where: $[C]$ is element capacitance matrix; $\dot{M}$ represents $\partial\{M\}/\partial t$; $\dot{T}$ represents $\partial\{T\}/\partial t$; $[K]$ is element conductance matrix; $\{F\}$ is the element force vector.

The backward difference method was used to approximate $\{T\}$ and $\{M\}$ in the i time step, so Eqn (6) becomes

$$([C] + \Delta t[K])\begin{Bmatrix} M \\ T \end{Bmatrix}_{i+1} = [C]\begin{Bmatrix} M \\ T \end{Bmatrix}_i + \Delta t\begin{Bmatrix} F_M \\ F_T \end{Bmatrix}_i \quad (7)$$

where F_M is element force derived from hygroscopic load and F_T is element force derived from thermal load.

Similar to Haghighi and Segerlind (1988), the concept of mass average moisture $\bar{M}$ was employed to describe the whole kernel moisture and used to verify the simulated data:

$$\bar{M} = \frac{\int_v M(r,z)\,\mathrm{d}m}{\int_v \mathrm{d}m} \quad (8)$$

where v denotes volumetric domain, and m the mass of an element.

The verified model was then applied to predict the MC gradients inside a rice kernel of variety Cypress (long-grain) used in this study. It was also used to predict the MC gradients of rice varieties Cypress and M202 (medium-grain) for the data published by Cnossen and Siebenmorgen (2000), Fan *et al.* (2000) and Pan *et al.* (2002). During computer simulation, a rice kernel was regarded as a three-layer elliptical-spherical body including hull, bran and endosperm, and shrinkage during drying was not considered. The dimensions (length, thickness and width) of rice kernels were measured in this study based on an average of 1000 kernels using a Satake Image Analyser (Satake Corporation, Tokyo, Japan). The resultant average length, width and thickness were: (1) for Cypress, 8·83, 2·49 and 1·93 mm; and (2) for M202, 7·85, 3·29 and 2·13 mm. For M202, kernel dimensions were measured of the same samples used by Pan *et al.* (2002). For Cypress, kernel dimensions were measured in this study, but it was assumed that the Cypress kernels used in the other studies had the same average dimensions. A two-dimensional axisymmetric finite element grid of a quarter section of the long-grain Cypress kernel is shown in *Fig. 1* as an example of the finite element division. The width and thickness were averaged to result in the short axis diameter in the two-dimensional simulation. The finite element mesh was generated automatically by the partial differential equation module of the Matlab software (The Mathworks, Inc., Natick, MA) with variable-sized triangular elements. The variable-sized elements were more advantageous over equal-sized ones for the ability to provide a better computational accuracy especially in some joint phases among the hull, bran and endosperm. The rice kernel properties used in this simulation were the same as reported by Yang *et al.* (2002).

Sarker *et al.* (1996), Chen *et al.* (1999) and Yang *et al.* (2002) reported that the greatest MC gradient existed in

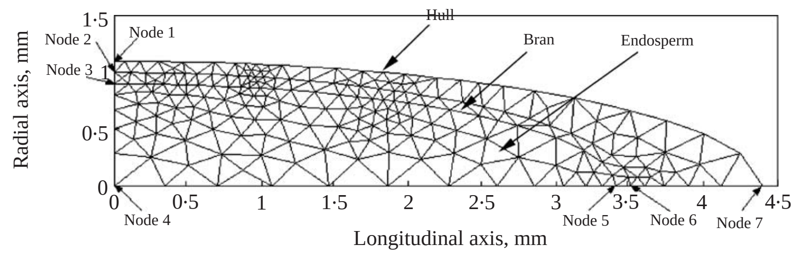

Fig. 1. Finite element mesh of a long-grain rough rice kernel (variety Cypress, $\frac{1}{4}$ section)

a direction perpendicular to the long axis of rice kernels and in the middle section of the longitudinal span of a kernel. Since the steepest gradient was near the surface of the endosperm, the maximal MC gradient was taken between nodes 2 and 4 in this study (*Fig. 1*). The benefit of using nodes 2 and 4 to define the maximal MC gradient was that it took into account the effect of rice bran, which was not considered by Sarker *et al.* (1996) who only determined MC gradients between the surface of the endosperm and the kernel centre.

MC gradients are theoretically defined as dM/dy (Sarker *et al.*, 1996; Yang *et al.*, 2002), where M is the d.b. MC at a node and y is the nodal coordinate relative to the centre of the kernel (node 4). It was found that when the MC gradient between nodes 2 and 4 was plotted against drying duration, the curves peaked after a certain drying duration. This particular time, termed in this study as the maximal MC gradient time, is a key target parameter of great interest, which can be determined by finite element analysis. It was confirmed in this study that plotting with either d.b. or wet basis (w.b.) MCs would result in the same time for the maximal MC gradient.

2.2. *Determination of HRY trend at various drying conditions*

The Cypress samples were dried in this study in a laboratory thin-layer drying system as described by Cnossen *et al.* (1999). The system consisted of a drying chamber in which air conditions could be specifically adjusted by a temperature and relative humidity (RH) control unit. Sixteen trays with perforated bottoms were used to hold rice samples in a thin-layer fashion, each holding a 90 g sample uniformly scattered on the perforated bottom. Two samples were removed at specified time intervals and mixed together. To maintain the same drying air distribution inside the drying chamber, dummy samples of the same weight were placed into the empty trays to replace the removed samples. Two 15 g samples were taken from each tray and used for MC measurement by oven method (Jindal & Siebenmorgen, 1987). The remainder of the sample was placed in an equilibrium-moisture-content chamber, maintained at 21°C and 55% RH, to gently dry to 12·5% w.b. MC.

A Satake laboratory huller (Satake USA, Houston, TX) was used to dehull the dried rice samples. Samples were milled for 30 s in a McGill No. 2 mill (Rapsco, Brookshire, TX), resulting in a degree of milling of 80–90 as measured by a Satake MM-1B milling meter (Satake USA, Houston, TX). Since the performance of the FOSS Graincheck 310 image analyser (Foss North America, Eden Prairie, MN) for measuring HRY was confirmed to be very comparable with that of the standard shaker table (Earp, 2000; Cnossen *et al.*, 2000a), HRY was determined using a FOSS Graincheck 310 image analyser in duplicate.

2.3. *Glass transition temperatures of rice kernels*

Perdon *et al.* (2000) measured the glass transition temperatures of rice kernels using two methods: a differential scanning calorimeter (DSC) and a thermal mechanical analyser (TMA). In this study, glass transition temperatures measured by DSC (*Fig. 2*) were used for constructing the glass transition state diagram. The glass transition temperatures of rice kernels measured by Perdon *et al.* (2000) reflected an overall response contributed by a combination of the components of a rice kernel including starch, protein, lipid, and other minor compositions.

3. Results and discussion

3.1. *Model verification*

Models have been verified with thin-layer drying experiments conducted at three drying conditions by Yang *et al.* (2002) for predicting the moisture and temperature distributions inside rice kernels. In this

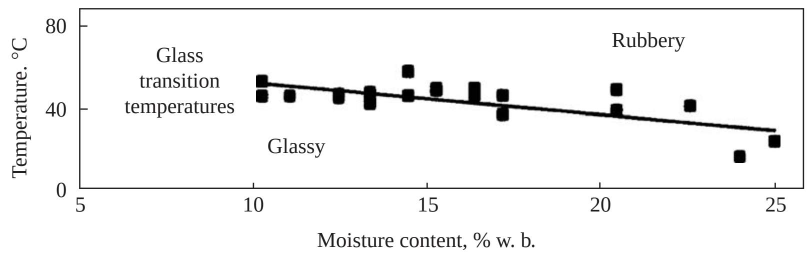

Fig. 2. The glass transition temperatures measured with a differential scanning calorimeter as a function of moisture content for brown rice kernels (Perdon, 1999; Perdon et al., 2000). Redrawn with permission

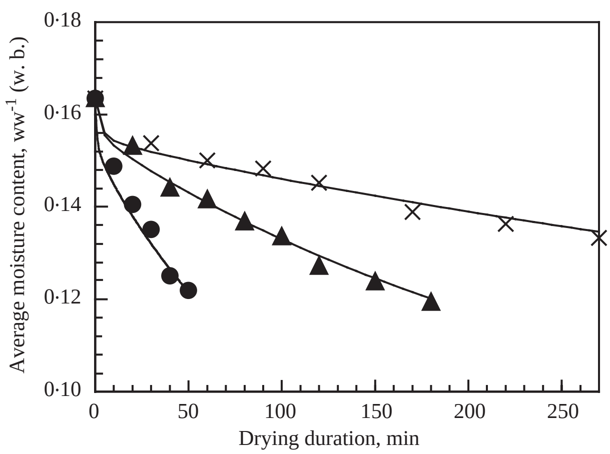

Fig. 3. Simulated (curves) and measured (symbols) average moisture contents at 16·4% w.b. initial kernel moisture content and three different drying conditions. ×, 34% relative humidity (RH) of drying air, 9·9% w.b. equilibrium moisture content (EMC) of rough rice corresponding to the drying condition, and 29°C drying air temperature (T_a); ▲, RH = 31%, EMC = 8·6% w.b., T_a = 43°C; ●, RH = 17%, EMC = 6·0% w.b., T_a = 54°C

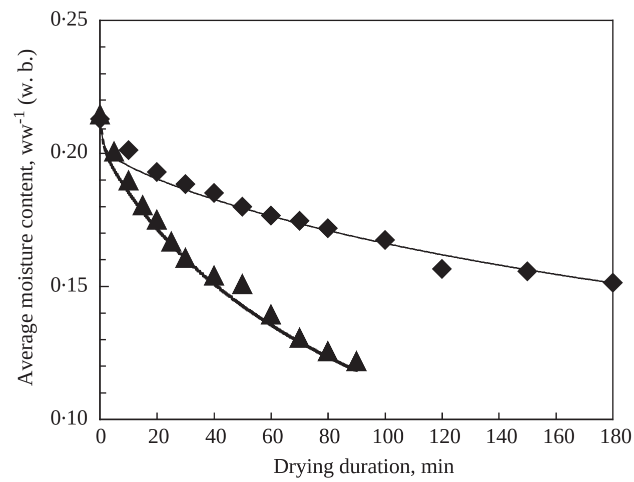

Fig. 4. Simulated (curves) and measured (symbols) average moisture contents at 21·4% w.b. initial kernel moisture content and two different drying conditions. ◆, 47% relative humidity (RH) of drying air, 10·9% w.b. equilibrium moisture content (EMC) of rough rice corresponding to the drying condition, and 38°C drying air temperature (T_a); ▲, RH = 17%, EMC = 5·9% w.b., T_a = 58°C

study, the models were verified against the thin-layer drying data in five more drying conditions, as presented in *Figs. 3* and *4*. These drying conditions are tabulated in Table 1.

The simulated results agreed well with the measured values under all the five experimental conditions tested, which further validated the finite element models developed by Yang *et al.* (2002) for determining MC gradients within a single rice kernel during drying.

3.2. *MC gradients and HRY trends*

As mentioned earlier, emphasis was placed on the MC gradients between nodes 2 and 4 (*Fig. 1*) in this study. The MC gradients *versus* drying duration in five different initial and drying conditions are shown in *Fig. 5*. A steep increase in MC gradients appeared in the early drying stage at a high temperature (*e.g.*, 58°C), followed by a slower decline after the MC gradients peaked. The maximal MC gradient time depended on the drying temperature, the kernel dimension, and the humidity of the drying air, as shown in Table 2.

Figure 6 depicts the measured HRY *versus* drying duration in the five drying and initial conditions mentioned earlier. As can be seen from *Fig. 6*, HRY decreased little during almost the entire drying process in the drying conditions of 29°C (34% RH), 38°C (47% RH) and 43°C (31% RH), respectively. As can be seen from *Fig. 2*, rice drying in these three drying conditions took place in the glassy region. This was because the statistical mean of T_g was about 45 and 38°C at 16·4 and 21·4% w.b. initial MCs, respectively, according to the DSC-measured T_g data (*Fig. 2*), and the three drying temperatures listed above all delimited rice to the glassy region. However, at higher drying temperatures, an apparent declining trend in HRY was observed. The decrease was marginal in the first 20–30 min drying period, but after that a dramatic drop in HRY was incurred. For example, for the drying conditions of 54°C

Table 1
Drying conditions for model verification

	Rice variety	*Initial MC, % w.b.*	*Drying temperature, °C*	*Air relative humidity, %*	*Sources*
Condition 1	Cypress	16·4	42	30	Yang *et al.* (2002)
Condition 2	Cypress	21·4	60	17	Yang *et al.* (2002)
Condition 3	Cypress	22·1	60	17	Yang *et al.* (2002)
Condition A	Cypress	16·4	29	34	This study
Condition B	Cypress	21·4	38	47	This study
Condition C	Cypress	16·4	43	31	This study
Condition D	Cypress	16·4	54	17	This study
Condition E	Cypress	21·4	58	17	This study

Note: MC, moisture content.

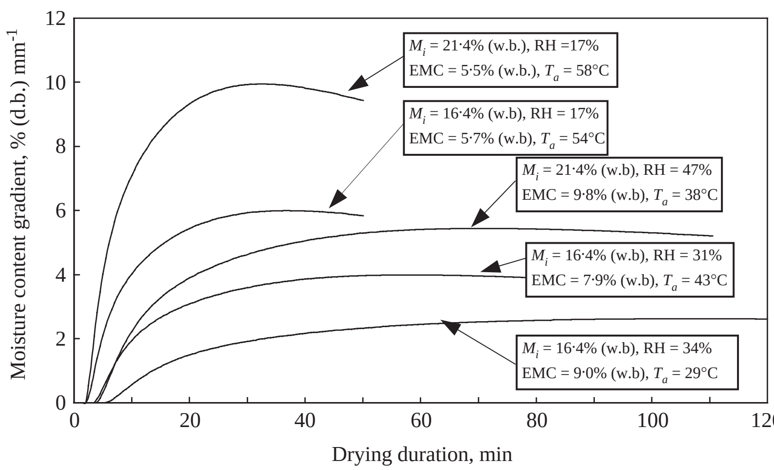

Fig. 5. Simulated moisture content gradients between node 4 and node 2 in Fig. 1 in five different drying and initial conditions; M_i, initial moisture content of the rice kernel; RH, relative humidity of drying air; EMC, the equilibrium moisture content of rough rice corresponding to the drying condition; and T_a, drying air temperature

Table 2
Drying behaviour of rice variety Cypress at the maximal moisture content gradient (MMCG) time in five different drying conditions

Drying temperature, °C	*RH, %*	*Initial moisture content, % (w.b.)*	*MMCG between nodes 2 and 4, % (d.b.) mm^{-1}*	*MMCG time, min*	*Average moisture content at MMCG, % (w.b.)*
29	34·2	16·4	2·6	106	14·6
38	47·0	21·4	5·4	70·5	18·4
43	30·9	16·4	4·0	57	14·0
54	16·8	16·4	6·0	35·5	13·0
58	17·0	21·4	9·9	31·5	16·5

Note: RH, relative humidity.

(17% RH) and 58°C (17% RH), there was a slight decrease in HRY within about 30 and 26 min, respectively, but after that HRY decreased dramatically and abruptly. Such a trend was also observed by Chen *et al.* (1999), Fan *et al.* (2000) and Pan *et al.* (2002). When the drying and initial conditions were superimposed on the rice state diagram in *Fig. 2*, it was found that HRY reduction occurred when drying had extended from the glassy region into the rubbery region and proceeded further thereafter. As mentioned earlier, the statistical mean of T_g is about 45 and 38°C at 16·4 and 21·4% MCs, respectively. Therefore, at 54 and 58°C drying temperatures, rice kernels had already experienced a state transition from glassy to rubbery.

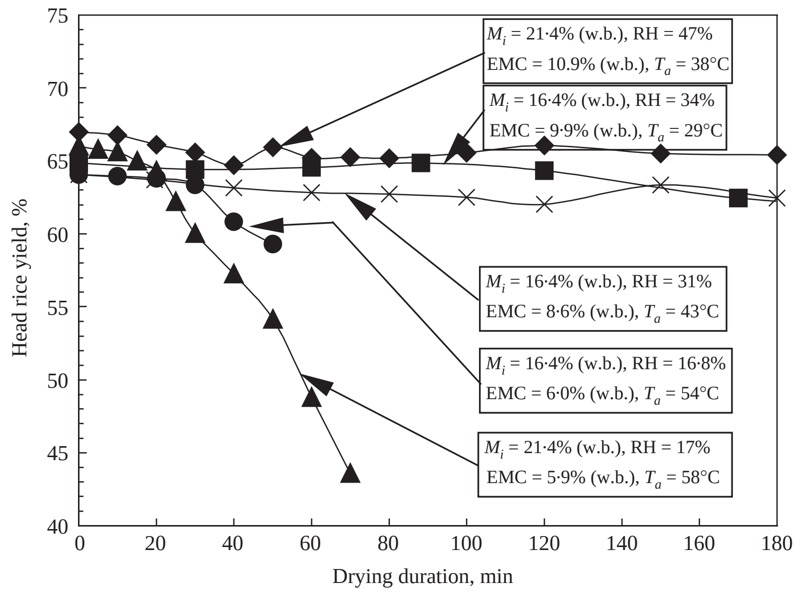

Fig. 6. Measured head rice yield versus drying duration in five different drying and initial conditions; M_i, initial moisture content of the rice kernel; RH, relative humidity of drying air; EMC, the equilibrium moisture content of rough rice corresponding to the drying condition; and T_a drying air temperature

In order to examine the relation of the maximal MC gradient to HRY reduction, *Figs. 5* and *6* were compared for the two cases: 54°C (16·8% RH) and 58°C (17% RH), where drying took place in the rubbery region. During comparison, the time range when the maximal MC gradient was reached was carefully checked against that when HRY started to decrease dramatically. As can be seen from both *Figs. 5* and *6*, the time at which HRY dropped dramatically coincided with the maximal MC gradient time. When drying duration exceeded the maximal MC gradient time, HRY kept decreasing at a much quicker rate.

3.3. *Effect of glass transition*

Arora *et al.* (1973) discovered, when drying rice variety Calora at 17% w.b. MC, that when temperature went beyond 53°C there was a rapid increase in the percentage of broken kernels. They also found that rice kernels exhibited a marked increase in rate of thermal expansion beyond 53°C. This temperature was characterised by them as a transition temperature indicating a change in intrinsic properties of rice kernels. Ekstrom *et al.* (1966) also reported such a transition temperature, 43°C, for maize (corn). Perdon (1999), Cnossen *et al.* (1999) and Yang *et al.* (2000) also reported that a state transition from rubbery to glassy inside the kernels could lead to rapid fissuring and decreased HRY as long as there were sufficient MC gradients built up inside the kernels.

The transition temperature (53°C) reported by Arora *et al.* (1973) for rice variety Calora at 17% w.b. MC was a bit higher than the statistical mean of T_g at the same MC for the Cypress used in this study (*i.e.* around 45°C). It was due probably to experimental method difference. However, both findings by Arora *et al.* (1973) and in this study clearly indicated that there existed a transition point during rice drying, which seemed to be the glass transition temperature of the kernels, although further experimental verification is needed to validate this inference. The findings suggested that if the drying duration per drying pass were so long as to render rice kernels past this transition point when drying took place in the rubbery region and yet no tempering was performed immediately after drying, HRY would incur a dramatic reduction. In other words, there existed a drying duration limit or percentage point of MC removal limit per drying pass, beyond which HRY would suffer a pronounced reduction if no tempering were to follow drying. According to the results obtained in this study, this drying duration limit per drying pass corresponded closely to the maximal MC gradient time, which suggested that the optimal time to terminate drying if no tempering would be performed after drying should be somehow around the maximal MC gradient time, if drying were to take place in the rubbery region.

3.4. *Validation with published data*

The HRY data for rice varieties Cypress (long-grain) (Cnossen & Siebenmorgen, 2000; Fan *et al.*, 2000) and M202 (medium-grain) (Pan *et al.*, 2002) reported in literature were used to validate the relationship between the maximal MC gradient time and the time when HRY dropped substantially, as discovered in this study. In other words, it was to verify that the percentage point of MC removal at the maximal MC gradient time closely approximated the percentage point of MC removal when the HRY started to drop dramatically. MC gradients were calculated by the finite element models discussed earlier for Cypress and M202 for the same drying conditions reported by Cnossen and Siebenmorgen (2000), Fan *et al.* (2000) and Pan *et al.* (2002). The maximal MC gradient times and the percentage points of MC removal at the maximal MC gradient times were recorded based on the simulation results. The actual percentage point of MC removal at the turn of HRY was visually determined from the reported data. Table 3 lists the predicted percentage points of MC removal at the maximal MC gradient times, the actually measured percentage points of MC removal at the turn of HRY and the related drying conditions. As an example, *Fig. 7* shows the trend of MC gradients and HRYs of Cypress at 60°C drying temperature, 17% RH and 20·6% w.b. initial MC, based on the data reported by Fan *et al.* (2000).

As can be seen from Table 3, the predicted and the measured percentage points of MC removal came fairly close to each other for Cnossen and Siebenmorgen (2000) and this study, with 0·4–0·5% in difference. For M202 used by Pan *et al.* (2002), most of the data came fairly close (0·1–0·6% in difference) except for one condition (*i.e.* the last but one row of Table 3) in which the percentage point of MC removal at the maximal MC gradient time (4·8%) had a 1·2% difference from the measured percentage point of MC removal at the turn of HRY. For Cypress used by Fan *et al.* (2000), a considerable difference between the percentage point of MC removal at the maximal MC gradient time and the measured percentage point of MC removal at the turn of HRY may be observed at first sight (Table 3). However, the difference might have actually been much smaller when the thickness of the rice bed (20 mm) used in the experiments of Fan *et al.* (2000), as opposed to a true thin layer—no more than three kernels thick according to ASAE (2001), was taken into account. During the drying of the 20 mm thick rice bed, a layer of 3 kernels thick (about 6 mm for Cypress) from the air inlet would be dried like a thin layer and behaved similarly in terms of the maximal MC gradient time and the HRY turning point, but the rest of the bed (*i.e.* from 6 to 20 mm) would be dried more slowly with less moisture removed given the same drying duration. Consequently, the maximal MC gradient time would still coincide with the time at which HRY dropped dramatically, because the HRY of the entire 20 mm bed responded in the same way as that of the thin layer (first 6 mm in the 20 mm bed). This has been proved by the closeness of the maximal MC gradient times and the HRY drop times

Table 3
Drying behaviour of rice varieties Cypress and M202 at the maximal moisture content gradient (MMCG) times in different drying conditions used by Fan *et al.* (2000), Cnossen and Siebenmorgen (2000), Pan *et al.* (2002), and this study

Source	*Drying temp., °C*	*RH, %*	*Initial moisture content, % (w.b.)*	*MMCG time, min*	*HRY drop time, min*	*Predicted PPMR at MMCG time, %*	*Measured PPMR at HRY turning point, %*
Cypress (long-grain, grown in Arkansas)							
Cnossen & Siebenm. (2000)	60	16·9	20·6	30·0	27	4·8	5
This study	54	17	16·4	35·5	30	3·4	3
This study	58	17	21·4	31·5	26	4·9	4.5
Fan *et al.* (2000)	60	17	19·8	30·0	30	4·6	3
Fan *et al.* (2000)	60	17	24·6	30·0	30	5·9	4
Fan *et al.* (2000)	60	17	16·5	30·0	30	3·6	2·5
M202 (medium-grain, grown in California)							
Pan *et al.* (2002)	43	35	20·9	76·5	N/A	3·5	4
Pan *et al.* (2002)	43	35	17·3	76·5	N/A	2·6	2
Pan *et al.* (2002)	43	35	22·7	76·5	N/A	3·9	4
Pan *et al.* (2002)	43	35	26·3	76·5	N/A	4·8	6
Pan *et al.* (2002)	50	28	26·3	57·0	N/A	5·4	6

Note: RH, relative humidity; HRY, head rice yield; PPMR, percentage point of moisture removal.

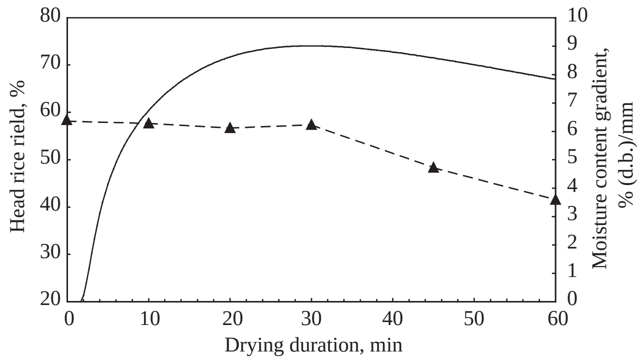

Fig. 7. Moisture content gradients (—) and head rice yield trends of Cypress as a function of drying duration; ▲ denotes the measured head rice yield and – – – denotes the trend of the head rice yield; data based on Fig. 4 in Fan et al. (2000)

for Fan *et al.* (2000) as shown in Table 3. However, when it comes to the measured percentage point of MC removal at the HRY turning point, the values would expect to be smaller, because the average MC of the 20 mm bed was much higher than that of the 6 mm thin layer. Hence, if the thickness of the bed is taken into consideration, the data by Fan *et al.* (2000) could also reasonably fit the simulation results obtained in this study. From *Fig. 7*, it can be seen that the maximal MC gradient time coincided very well with the turning point in the HRY curve. Data in Table 3, *Figs. 5–7* all indicate that the maximal MC gradient time closely approximated the time when HRYs started to drop dramatically, at least for the rice varieties Cypress and M202, although whether this relationship can be generalised to other varieties still requires experimental verification.

3.5. *Significance of the findings*

The findings in this study helped explain HRY variations as a result of different drying conditions. The information would be very useful for designing an optimized rice drying and tempering process. A significant contribution of this study to rice drying technology is that the maximal MC gradient time would provide, when used in conjunction with rice graders to separate rice into relatively uniform size fractions, an alternative parameter to effectively control the retention time of rice in a dryer to minimise rice breakage susceptibility and increase rice milling quality. It also shows the possibility of predicting the maximum allowable percentage point of MC removal or retention time per drying pass during heated-air drying of rice without significantly affecting HRY for a specific rice variety by computer modelling without the need of actually measuring the HRY. This would be very useful for drying equipment manufacturers, rice millers and rice producers.

4. Summary and conclusions

Mathematical models describing heat and moisture movements inside a rice kernel during drying were solved using the finite element method, and the intra-kernel moisture content gradients during drying were predicted and analysed. The relation of intra-kernel moisture content gradients and glass transition temperatures to head rice yield variations during drying was examined. It was found that when a drying temperature was below the glass transition temperature of rice kernels and the drying took place in the glassy region, head rice yield reduced little with an increased drying duration. When rice was dried in the rubbery region and no tempering was performed immediately after drying, there existed a limit for the percentage points of moisture content removal per drying pass beyond which head rice yield would incur a dramatic decrease. This turning point in head rice yield trend was found to coincide with the time when the maximum moisture content gradient occurred. Such a relation was validated with the head rice yield data of varieties of Cypress and M202 measured in this study and cited from literature.

References

Arora V K; Henderson S M; Burkhardt T H (1973). Rice drying cracking versus thermal and mechanical properties. Transactions of the ASAE, **16**(2), 320–327

ASAE (2001). ASAE Standard S448: Thin-Layer Drying of Grains and Crops. American Society of Agricultural Engineers, St. Joseph, MI

Banaszek M M; Siebenmorgen T J (1993). Individual rice kernel drying curves. Transactions of the ASAE, **36**(2), 521–527

Brooker D B; Bakker-Arkema F W; Hall C W (1992). Drying and Storage of Grains and Oilseeds. Van Nostrand Reinhold, New York, NY

Chen H; Siebenmorgen T J; Marks B P (1997). Relating drying rate constant to head rice yield reduction of long-grain rice. Transactions of the ASAE, **40**(4), 1133–1139

Chen H; Siebenmorgen T J; Yang W (1999). Finite element simulation to relate head rice yield reduction during drying to internal kernel moisture gradient and rice state transition. ASAE Paper No. 99-6156

Cnossen A G; Siebenmorgen T J; Yang W (1999). Incorporating the glass transition temperature concept in rice drying and tempering to optimize moisture removal and milling quality. ASAE Paper No. 99-6022

Cnossen A G; Siebenmorgen T J (2000). The glass transition temperature concept in rice drying and tempering: effect on milling quality. Transactions of the ASAE, **43**(6), 1661–1667

Cnossen A G; Siebenmorgen T J; Yang W (2000a). Evaluation of two methods for separating head rice from brokens for head rice yield determination. Proceedings of 2000 Rice Technical Working Group Conference, Biloxi, MS

Cnossen A G; T J Siebenmorgen; Yang W; Bautista, R C (2000b). An application of glass transition temperature to explain rice kernel fissure occurrence during the drying process. Drying Technology, **19**(8), 1661–1682

Earp C F (2000). Use of Foss Graincheck 310 for measuring rice milling yields. Proceedings of 2000 Rice Technical Working Group Conference, Biloxi, MS

Ekstrom G A; Lijedahl J B; Peart R M (1966). Thermal expansion and tensile properties of corn kernels and their relationship to cracking during drying. Transactions of the ASAE, **9**(2), 556–561

Fan J; Siebenmorgen T J; Yang W (2000). A study of head rice yield reduction of long- and medium-grain rice varieties in relation to various harvest and drying conditions. Transactions of the ASAE, **43**(6), 1709–1714

Haghighi K; Segerlind L J (1988). Modeling simultaneous heat and mass transfer in an isotropic sphere—a finite element approach. Transactions of the ASAE, **31**(2), 629–637

Irudayaraj J; Haghighi K; Stroshine R L (1992). Finite element analysis of drying with application to cereal grains. Journal of Agricultural Engineering Research, **53**(2), 209–229

Jia C-C; Sun D; Cao C W (2000a). Mathematical simulation of stresses within a corn kernel during drying. Drying Technology, **18**(4), 887–906

Jia C-C; Sun D; Cao C W (2000b). Mathematical simulation of temperature and moisture fields within a grain kernel during drying. Drying Technology, **18**(6), 1305–1325

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

Kunze O R (1979). Fissuring of the rice grain after heated air drying. Transactions of the ASAE, **22**(5), 1197–1201, 1207

Lan Y; Nguyen C N; Kunze O R; Kocher M F; Lague C (2000). Theoretical analysis of stress distribution in rice kernel from moisture adsorption. Proceedings of 2000 Rice Technical Working Group Conference, Biloxi, MS

Litchfield J B; Okos M R (1988). Prediction of corn kernel stress and breakage induced by drying, tempering and cooling. Transactions of the ASAE, **31**(2), 585–594

Misra R N; Young J H; Hamann D D (1981). Finite element procedures for estimating shrinkage stresses during soybean drying. Transactions of the ASAE, **24**(3), 751–755

Pan Z; Wei L; Thompson J F (2002). Effect of moisture removal by heated air on rice milling quality and moisture distribution with simulated column drying. Abstract, the 2002 Rice Technical Working Group Conference, Little Rock, AR, February 24–27, 2002

Perdon A A (1999). Amorphous state transition in rice during the drying process. PhD Dissertation, University of Arkansas, Fayetteville, AR, USA

Perdon A A; Siebenmorgen T J; Mauromoustakos A (2000). Glassy state transition and rice drying: development of a brown rice state diagram. Cereal Chemistry, **77**(6), 708–713

Rao V N N; Hamann D D; Hammerle J R (1975). Stress analysis of a viscoelastic sphere subjected to temperature and moisture gradients. Journal of Agricultural Engineering Research, **20**(3), 283–293

Sarker N N; Kunze O R; Strouboulis T (1996). Transient moisture gradients in rough rice mapped with finite element model and related to fissures after heated air drying. Transactions of the ASAE, **39**(2), 625–631

Thompson R A; Fortes G H (1963). Stress cracks and breakage in artificially dried corn. Marketing Research Bulletin No. 631, TFRD, AMS, USDA

USDA (1990). Inspection Handbook for the Sampling, Inspection, Grading, and Certification of Rice. HB918-11, Agriculture Marketing Service, Washington, DC

Yang W; Jia C; Siebenmorgen T J; Howell T A; Cnossen A G (2002). Intra-kernel moisture responses of rice to drying and tempering treatments by finite element simulation. Transactions of the ASAE, **45**(4), 1037–1044

Yang W; Siebenmorgen T J; Jia C; Howell T A; Meullenet J F; Cnossen A G (2000). Rice kernel drying behaviour in a cross-flow dryer in relation to a glass transition state diagram. Proceedings of 2000 Rice Technical Working Group Conference, Biloxi, MS

Zoerb G C (1958). Mechanical and rheological properties of grain. PhD Thesis, Michigan State University, East Lansing, MI