
Volume 113, Issue 4, December 2012
ISSN 0260-8774
ELSEVIER
journal of
food engineering

Journal of Food Engineering 113 (2012) 559–568

Contents lists available at SciVerse ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Rice degree of milling effects on hydration, texture, sensory and energy characteristics. Part 1. Cooking using excess water

M.A. Billiris [a], T.J. Siebenmorgen [a,*], J.-F. Meullenet [a], A. Mauromoustakos [b]

[a] Department of Food Science, University of Arkansas, Fayetteville, AR 72704, USA
[b] Agricultural Statistics Lab., University of Arkansas, Fayetteville, AR 72701, USA

ARTICLE INFO

Article history:
Available online 16 July 2012

Keywords:
Cooking energy
Rice cooking kinetics
Parboiled rice
Non-parboiled rice
Cooked-rice texture and flavor

ABSTRACT

The purpose was to assess the effect of degree of milling (DOM) on cooking kinetics, sensory attributes, and energy requirements when cooking rice in excess water. Commercial milling equipment was adjusted to produce parboiled and non-parboiled rice samples that were milled to varying DOMs, including brown rice lots having no milling. Surface lipid content (SLC) ranged from 0.15% to 0.55% for non-parboiled rice and from 0.40% to 0.95% for parboiled rice. The percentage gelatinized kernels, moisture content, peak force and sensory attributes were determined as a function of cooking duration for all samples. The cooking duration required to attain 'well-cooked' rice was determined, after which the energy required for cooking was measured. Within the SLC range tested, DOM did not affect cooking kinetics, texture and flavor of rice. Non-parboiled brown rice required the most energy, expressed as energy per unit mass of uncooked rice, to be cooked, followed by parboiled brown, parboiled milled and non-parboiled milled rice.

1. Introduction

Rice milling consists of removing the embryo and bran layers from brown rice, after the hull is separated from rough rice (Bond, 2004). The amount of bran left on kernels after milling, referred to as the degree of milling (DOM), is often dictated by consumer requirements. Surface lipid content, often used as an indicator of DOM, decreases as milling progresses.

Milling rice to lesser degrees, that is, leaving more bran on milled kernels, can lead to greater milling yields and human nutritional benefits, as well as potential energy savings (Cooper and Siebenmorgen, 2007; Lanning and Siebenmorgen, 2011; Roy et al., 2008). From an energy-use standpoint, milling rice to lesser degrees requires shorter milling durations (Cooper and Siebenmorgen, 2007), thus consuming less energy during milling operations. However, rice milled to lesser degrees may require more energy for cooking. The latter is affected by the duration required to cook rice, which is determined by cooking kinetics and desired sensory characteristics. Desikachar et al. (1965) found that for a given cooking duration, swelling ratio, an indicator of water absorption, increased as DOM increased, but the increase was not significant beyond 75% of bran removal. They explained that fat and wax present in the bran layers hinder water absorption into the kernels; when fat and wax were removed from brown rice using acetone, the water absorption rate significantly increased.

Mohapatra and Bal (2006) reported that cooking duration, based on the point at which 90% of kernels are gelatinized, decreased as DOM increased. Juliano and Perez (1983) concluded that for cooking temperatures below 100 °C, starch reactivity with water was the limiting factor affecting cooking rate of milled rice. However, if leaving more bran on kernels decreases the water absorption rate into kernels (Desikachar et al., 1965), it is reasoned that absorption kinetics at the kernel surface would be the limiting factor affecting cooking rate at lesser milling degrees.

Degree of milling affects pasting properties, which are often used as indicators of rice behavior during further processing. Perdon et al. (2001) found that peak viscosities increased with increasing DOM. Mohapatra and Bal (2006) reported that instrumental hardness and adhesiveness of cooked rice decreased as the DOM increased. These effects were influenced by proximate composition. Saleh and Meullenet (2007) found that instrumental firmness of cooked rice decreased from 110 to 90 N when SLC decreased (DOM increased) from 0.6% to 0.2% for two long-grain cultivars. Champagne et al. (1997) and Park et al. (2001) found that cooked rice flavor attributes, as determined by a sensory panel, were affected by DOM. In addition, Champagne et al. (1997) reported that DOM effects are dependent on rice cultivar and production location.

Roy et al. (2004) found that parboiling affects cooking duration and textural properties of rice, and that parboiled rice required

* Corresponding author. Tel.: +1 479 575 2841.
E-mail address: tsiebenm@uark.edu (T.J. Siebenmorgen).

0260-8774/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jfoodeng.2012.07.005

more energy to be cooked than non-parboiled rice. Bhattacharya and Sowbhagya (1971) explained that because parboiled rice has a slower water uptake rate than non-parboiled rice, longer durations are required for parboiled rice to achieve a given texture, thus the energy required for cooking will be greater.

The literature available on milling-degree effects on cooking kinetics, texture, flavor and energy requirements is limited, thus justifying further work based on potential energy savings and nutritional benefits.

A two-part study was conducted with the overall goal of assessing rice milling degree effects on cooking characteristics and energy requirements using different cooking methods for both non-parboiled and parboiled rice. Reported herein are findings when cooking rice in excess water; a companion manuscript reports on findings when cooking rice using controlled water-to-rice-ratios. The objectives of this manuscript were to: (1) determine cooked-rice hydration, gelatinization, and instrumental texture responses of rice milled to various degrees; (2) determine cooked rice texture and flavor of rice that was milled to various degrees using a sensory panel; (3) determine the duration required to obtain 'well-cooked' rice, from which cooking energy requirements can be calculated.

2. Materials and methods

2.1. Rice samples

Lots of long-grain, milled rice were collected from a commercial mill at Jonesboro, AR in spring, 2010. A three-break, water-misting milling system (Satake[1] VTA, VBF, KB-40) was adjusted to produce non-parboiled rice samples that were milled to head rice SLC levels of 0.15%, 0.20%, 0.40% and 0.55%, as measured using a lipid analysis procedure (Lanning and Siebenmorgen, 2011). A non-milled, brown rice sample from the same milling run was also taken, with a total lipid content of 2.30%, as determined using the same procedure, but with brown rice flour, rather than an intact, head rice sample. Initial moisture content (MC) of samples was 16%[2]. At the same commercial facility, but with a different triple-break milling system (Satake VTA, KB-40, KB-40), parboiled brown rice (total lipid content of 2.30%) and milled rice samples were obtained in the same manner with resulting head rice SLCs of 0.40%, 0.45%, 0.70% and 0.95%. Initial MC of samples was 14%. Brokens were removed from the samples using a rice grader (Model TRG 05A, Satake Engineering Co., Tokyo, Japan). The remaining head rice was refrigerated at approx. 5 °C in a sealed container. The samples were removed from the cooler and allowed to equilibrate to approx. 21 °C for 24 h before performing subsequent experiments.

The commercially-milled rice samples, while all of a long-grain type, were of unknown cultivar. Lucisano et al. (2009) and Juliano (1971) reported that cooking duration is cultivar specific. However, because the five lots of the parboiled rice and the five non-parboiled lots were obtained within a short period from the same large milling runs, it was assumed that each lot set was of the same cultivar or cultivar mixture. Thus, differences in cooking kinetics, instrumental texture, sensory characteristics, and energy use were presumed to be due to DOM effects. Fig. 1 shows the experimental design for Part 1 of this study, in which rice was cooked in excess water. The tests depicted in Fig. 1 are described in the following sections.

2.2. Cooking kinetics and instrumental texture

The number of gelatinized kernels as a function of cooking duration was determined using a method in which cooked rice kernels are compressed and visually inspected, as described by Ranghino (1966), Juliano (1985) and Desikachar and Subrahmanyan (1961). The method comprises adding 5 g of head rice to 100 mL of boiling water in a 250-mL beaker. After 10 min of cooking on a hot plate (VWR Scientific Products, USA), ten kernels were removed from the boiling mixture with a spoon, pressed between glass plates (5 cm × 5 cm) by hand and the number of kernels having "starchy" cores, indicating that gelatinization had not occurred, was counted. The procedure was repeated every minute until no starchy cores existed. The test was replicated five times for each cooked-rice subsample. This method was referred to as the gelatinization-kinetics (GK) method.

Cooked-rice MC, which was used as an indicator of water absorption rate, and instrumental texture were determined simultaneously. Forty g of head rice were added to 350 mL of boiling water in a 400-mL beaker. After 12 min of cooking on a hot plate, approx. 5 g of kernels were removed from the boiling mixture with a spoon and placed in a strainer for 3–5 s. For the MC analysis, approx. 4 g of cooked rice were placed in a previously-weighed aluminum pan (5-cm diameter) and then covered with another aluminum pan. After 15 min, the mass of the pan and cooked rice was taken. The weighed pans and rice were placed in an oven at 130 °C for 24 h, and then placed in a desiccator for 15 min and weighed. Moisture content was expressed on a wet-weight basis.

The remaining cooked rice kernels in the strainer were immediately placed in a plastic bag, the air was removed and the bag was sealed and stored at lab temperature (~20 °C). After 30 min, 10 kernels were removed from the plastic bag, weighed, and placed on the aluminum plate of a texture analyzer (TA-XT2i, Texture Technologies Corp., Godalming, Surrey, UK). Texture analysis was performed using a 50-kg load cell under a compression test mode, using a 10-cm (4-in.) diameter, 0.60-cm (0.25-in.) thick aluminum probe, with a speed of 5 mm/s. The kernels were compressed to 0.3 mm, after which the probe was held for 5.0 s and returned at 0.5 mm/s. The maximum compression force (peak force) of the test run was used to quantify cooked rice hardness.

2.3. Cooking duration determination using cooking kinetics and instrumental texture

The duration required to obtain 'well-cooked' rice, which was assumed to be the duration at which the crystalline structure of starch was completely disrupted, was determined first from the above instrumental tests. For non-parboiled rice, three instrumental approaches were used. First, the duration required to gelatinize 100% of the kernels was used as an indicator of 'well-cooked' rice (Fig. 2a). Secondly, it was hypothesized that the drastic change in the slope of the MC vs. cooking duration curve would indicate the point at which the rice sample was 'well-cooked'. To determine this inflection point, a model consisting of two linear lines with different slopes (Fig. 2b), was developed using JMP Pro 9 (Eqs. 1-3).

$$\text{Line 1 (Rapid increase in MC)}: y = b_r - s_r \times d \quad (1)$$

$$\text{Line 2 (Slow increase in MC)}: y = b_s - s_s \times d \quad (2)$$

The intersection of the two lines (d_i) occurs when y, the MC, is the same for both lines:

$$b_r - s_r \times d_i = b_s - s_s \times d_i$$

Rearranging,

$$d_i = \frac{b_r - b_s}{s_r - s_s} \quad (3)$$

where; d is the cooking duration; s_r is the slope of the line with greater slope (rapid increase); s_s is the slope of the line with lesser slope (slow increase); b_r is the intercept of the line with greater

[1] Mention of a commercial name does not imply endorsement by authors.

[2] All moisture contents are reported on a wet basis.

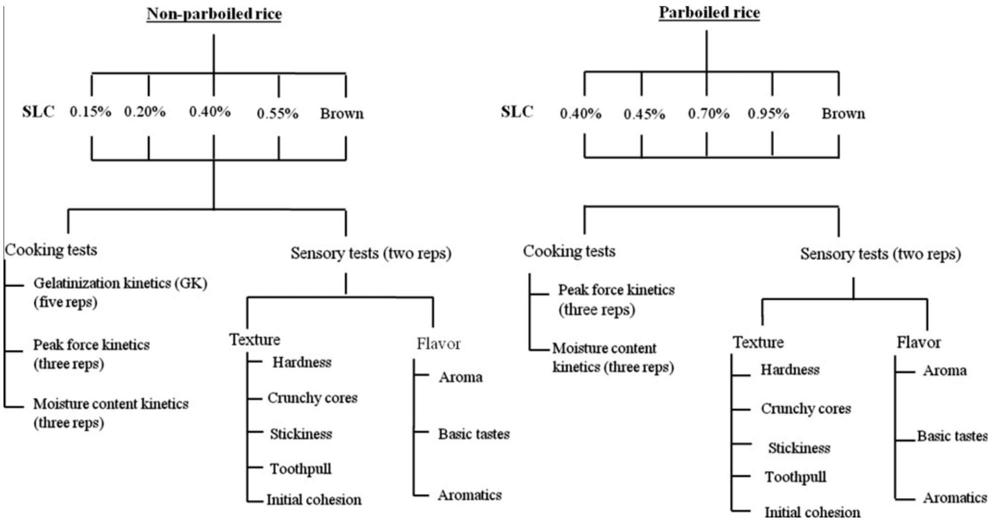

Fig. 1. Experimental design for tests in which rice at the indicated surface lipid contents (SLCs) was cooked using excess water.

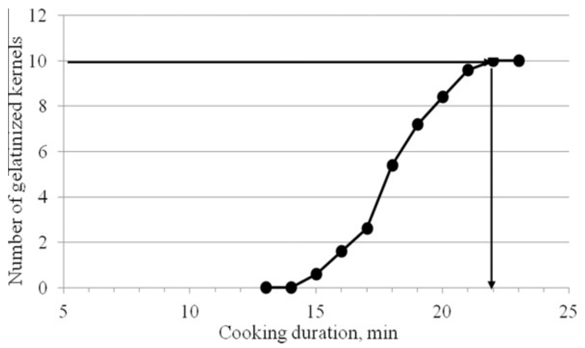

Fig. 2a. An illustration of using the method of Desikachar and Subrahmanyan (1961) to determine the duration required to attain 'well-cooked' rice (100% gelatinized kernels).

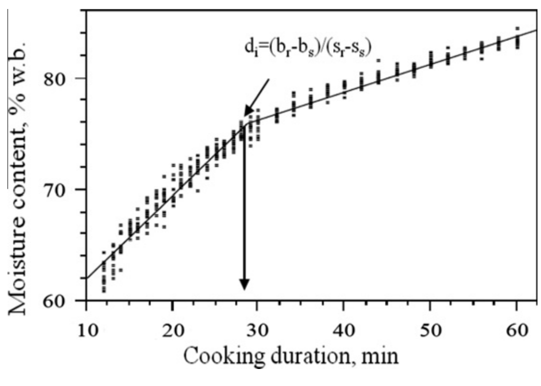

Fig. 2b. An illustration of applying Eq. (3) to a moisture content vs. cooking duration curve to estimate the inflection point, which was hypothesized to represent the duration at which rice was 'well-cooked'.

slope; b_s is the intercept of the line with lesser slope; d_i is the cooking duration corresponding to the intersection of the two lines (inflection point).

Applying Eq. (3) to the MC curves was used as the second approach to determine the cooking durations required to achieve 'well-cooked' rice. This same procedure was applied to the peak force vs. cooking duration curves as a third estimation of the duration required to attain well-cooked rice. Because parboiled rice is already pre-gelatinized, the number of gelatinized kernels could not be used to determine the durations required to achieve 'well-cooked' parboiled rice. As such, these durations for parboiled rice were determined only from MC and peak force kinetics data, as described above for non-parboiled rice.

2.4. Sensory tests

Sensory tests, in which the effects of milling degree on cooked rice texture and flavor attributes were evaluated directly by human subjects, complemented the information obtained from gelatinization, MC and peak force kinetics data. For this purpose, the GK-method and instrumental-texture data were first analyzed to establish the cooking durations used to prepare rice for presentation to the panel. The panel assessed texture and flavor attributes of rice samples with various SLCs cooked for the durations indicated in Fig. 3.

2.4.1. Sensory panel

An 11-member sensory panel, from the Sensory Science and Rheology Program of the Food Science Department of the University of Arkansas, was trained using a modified Spectrum Method (Meilgaard et al., 1999) using product-specific references. References were available to panelists throughout the tasting session. Cooked rice samples were presented to panelists in test blocks and each test block was carried out in the same session (Fig. 3). Each block was replicated on separate days. Because texture and flavor tests were carried out on different days, 12 sessions were conducted (3 blocks representing the various rice set groupings (Fig. 3) × 2 sensory tests (texture and flavor) × 2 replications). Attribute definitions, evaluation techniques and references for texture and flavor tests were obtained from the work of Suwansri et al. (2002) except for references and scales used for cooked rice texture evaluation, which are shown in Table 1. Intensities for basic tastes were obtained from Meilgaard et al. (1999) and intensities for aromatics were based on the Universal scale (kracker was a 3.0, applesauce a 7.0, orange juice a 10.0, grape juice a 14.0 and cinnamon gum a 16.0).

2.4.2. Sample preparation for the sensory panel

Head rice was cooked in a rice cooker (RC 101 type 2, Rival, Milford, MA) using a 3.5–1.0 water-to-rice mass ratio for non-parboiled milled rice and a 4.0–1.0 water-to-rice mass ratio for parboiled milled rice and both parboiled and non-parboiled brown

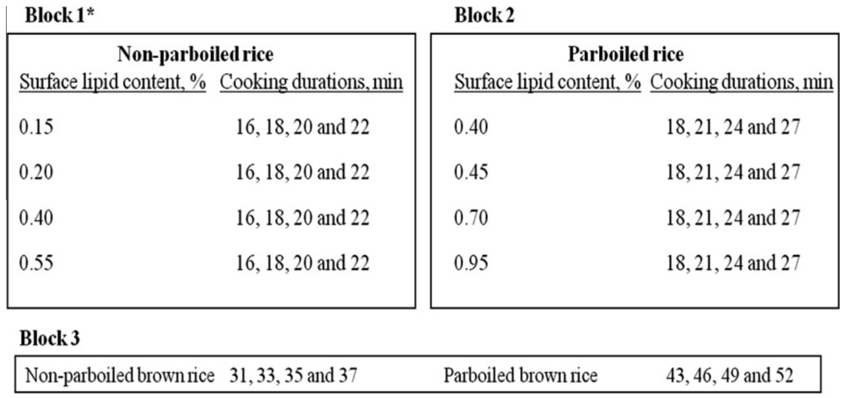

Fig. 3. Experimental design of sensory texture and flavor tests for non-parboiled and parboiled rice. *Both texture and flavor sensory tests were conducted within the test blocks indicated. Each test block was carried out in the same session and repeated on different days.

Table 1
References and scales used by the sensory panel to evaluate cooked rice texture.

Attribute	Reference code*	Scale
Initial cohesion	Rice C	1.0
	Rice A	3.0
	Rice E	11.0
	(loose – tight)	
Hardness	Rice E	1.0
	Rice A	4.0
	Rice C	5.0
	Rice D	10.0
	(soft – hard)	
Crunchy cores	Rice A	5.0
	Rice D	12.0
Tooth pull	Rice C	2.0
	Rice A	4.0
	(none – very sticky)	
Manual Stickiness	Rice A	5.0
	(none – very sticky)	
*Reference code	Rice description	Water-to-rice ratio – cooking duration
Rice A	Riceland Brown –300 grams	3.5:1–35 min
Rice C	Uncle Ben's Brown –300 grams	3.5:1–25 min
Rice D	Riceland Brown –300 grams	3.5:1–25 min
Rice E	Riceland x-long white –300 grams	3.5:1–25 min

rice. The mass of water required to reach the desired water-to-rice ratio was placed in the rice cooker at room temperature (~20 °C), the rice cooker turned on, and the water heated to a boil. Three-hundred grams of head rice were then added to the boiling water and the boiling mixture was covered with the rice cooker lid. Rice was cooked for the corresponding cooking duration (Fig. 3), removed from the boiling mixture and placed in a strainer for 5 s to drain excess water. Approx. 55 g of cooked rice were placed in a 113-g (4-oz) soufflé cup and covered with a plastic lid. For flavor tests, the soufflé cup and the plastic lid were substituted by a 113-g (4-oz) glass bowl and glass lid. Rice was allowed to cool for 10 min before being presented to the panel. It is noted that instrumental hardness tests were performed after various cooling durations ranging from 10 to 40 min; there were no statistical differences in hardness. Thus, the instrumental hardness (peak force) tests described previously, in which rice was cooled for 30 min prior to testing, should be comparable to the hardness values determined by the sensory panel after cooling for 10 min. For each session, samples were presented to the panelists in a random order.

2.5. Energy tests

Head rice was cooked in a rice cooker (RC 101 type 2, Rival, Milford, MA) using water-to-rice mass ratios of 3.50, 3.75 and 4.00. The three water-to-rice ratios were included in the procedure to ensure that the energy tests comprised excess-water cooking in the rice cooker. Rice from each set was cooked at each water-to rice ratio in the rice cooker for the duration to attain well-cooked rice, determined from the gelatinization, peak force or MC tests (Fig. 2a and b). After each cooking run, a visual observation was made to determine whether liquid remained in the cooker. It was determined that the least water-to-rice ratio that allowed water in the cooker at the end of a run, and thus represents excess-water cooking was the 3.50 water-to-rice ratio. To measure energy requirements to cook rice using excess-water method, the mass of distilled water at ~20 °C required to reach the desired water-to-rice ratio was placed in the rice cooker at room temperature, the rice cooker was turned on, and the water heated to 98 °C. As soon as the water reached 98 °C, an energy reading was taken using a power meter (PROes, Electronic Educational Devices, Inc., Denver, CO) that had an accuracy of ±1.5% of the reading, and then 300 g of head rice were added to the heated water in the rice cooker. Rice was cooked for the duration required to obtain 'well-cooked' rice. This duration depended on the rice set being cooked and the evaluation method used to indicate well-cooked rice; the durations were 22, 26, 29 and 34 min for non-parboiled milled, parboiled milled, parboiled brown and non-parboiled brown rice. The cumulative energy was taken after rice was cooked for a given duration.

Moisture content was determined in triplicate at the end of cooking.

Because the rice cooker was inside a laboratory maintained at ~20 °C, it was expected that day-to-day variation due to surroundings were negligible. However, to assess the variability of the energy measurements, eight replications were performed to measure the energy required to heat water to 98 °C in the rice cooker on different days. To heat 1,125 g of water (amount of water corresponding to a 3.75 water-to-rice ratio) to 98 °C, the mean of energy measurements was 139 Wh, with a SD of 3 Wh. This variability level was deemed acceptable for the purposes of this study.

All statistical analyses were performed using software (JMP Pro 9, SAS Institute, Inc., Cary, NC) and the *p*-value was set at 0.05. A completely randomized design was used for physical and instrumental tests and a randomized block design, in which panelists were considered as blocks, was used for descriptive sensory evaluation. Analysis of variance (ANOVA) was used to assess the overall effect of SLC and cooking duration. The Tukey test was performed to assess significance of differences among individual means. Differences among cooking durations to obtain 'well-cooked' rice were assessed using confidence intervals.

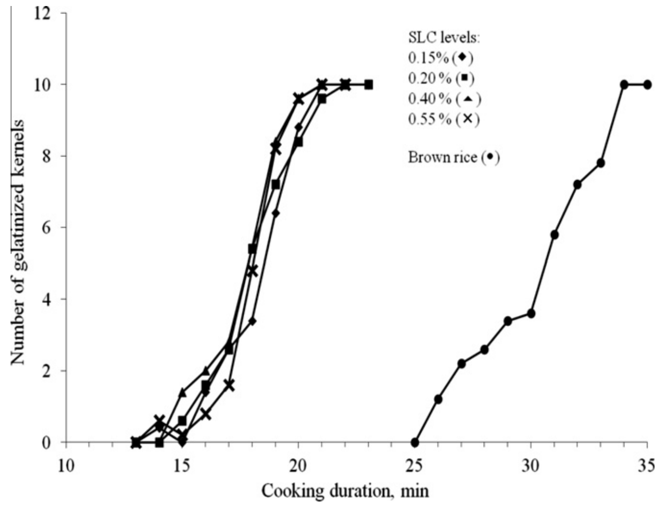

Fig. 4. Number of gelatinized kernels as a function of cooking duration for non-parboiled rice that had been milled to the indicated surface lipid content (SLC) levels. Data points are means of five replications.

3. Results and discussion

3.1. Cooking kinetics

Fig. 4 shows that the number of gelatinized kernels of non-parboiled milled rice increased as cooking duration increased in a sigmoid trend; all kernels were gelatinized after approx. 22 min. Similar trends were found by Lucisano et al. (2009). Gelatinization kinetics of milled rice with SLCs ranging from 0.15% to 0.55% were equivalent, indicating that milling non-parboiled rice to a lesser degree (up to 0.55% SLC) did not affect gelatinization kinetics. However, the rate of gelatinization of non-parboiled brown rice was considerably less than that of non-parboiled milled rice; 34 min of cooking were required to gelatinize all brown rice kernels (Fig. 4). Desikachar et al. (1965) found that water absorption into brown rice kernels is hindered due to the presence of fat and wax in the bran. In particular, the hydrophobic waxy cuticle (Champagne et al., 2004), a component of the outer surface of brown rice kernels, could offer a physical barrier to water absorption. Therefore, the slow gelatinization rate of the starch in brown rice kernels could be due to limited water transfer at the brown rice kernel surface; this is in agreement with the MC results shown in Fig. 5.

Moisture content of cooked, non-parboiled milled rice increased rapidly as cooking duration increased, reaching a near-equilibrium MC of approx. 87% after 50 min of cooking (Fig. 5). Similar trends were reported by Das et al., 2006; Desikachar et al., 1965 and Roy et al., 2008. Fig. 5 shows that leaving more bran on milled rice kernels, up to 0.55% SLC, did not affect water absorption rate, based on the congruence of the moisture absorption curves for each SLC level. Desikachar et al. (1965) reported that swelling ratio increased significantly up to 75% bran removal (as bran removal increases SLC decreases) but further bran removal did not affect swelling ratio when cooking in excess water. The MC of non-parboiled brown rice was less than that of milled rice at any cooking duration; at 60 min of cooking, the brown rice MC was approx. 78%. Ondier et al. (accepted for publication) found that equilibrium MCs of brown rice were significantly less than those of milled rice.

Peak force, which is affected by sample mass, was expressed on a per unit mass of cooked kernels basis to reduce variability. Peak force decreased exponentially as cooking duration increased (Fig. 5), which is in agreement with Juliano and Perez (1983) and Roy et al. (2008) who showed that peak force decreased exponentially as water-to-rice ratio increased until reaching a plateau (an increase in water-to-rice ratio implies an increase in cooking duration). In addition, Fig. 5 shows that peak force vs. cooking duration curves overlapped for rice milled to the various SLC levels, indicating that milling degree (up to 0.55% SLC) did not affect peak force kinetics of non-parboiled rice.

Non-parboiled brown rice showed considerably greater peak force values than non-parboiled milled rice at any given cooking duration (Fig. 5). The lesser MC (Fig. 5) and number of gelatinized kernels (Fig. 4) of brown rice at a given cooking duration could explain the greater peak force. In addition, the presence of the intact bran layers, which comprise considerable fiber, lipids and proteins (Champagne et al., 2004), would be expected to confer a greater texture to brown rice kernels because the bran layers may constrict swelling, limiting water absorption and thus increasing peak force.

Fig. 6 shows that MC and peak force kinetics of parboiled rice followed the same trends as those of non-parboiled rice. Parboiled milled rice MCs and peak force data (Fig. 6) showed less variability than those of non-parboiled milled rice (Fig. 5), even though parboiled rice samples spanned a wider range of SLCs (0.40–0.95%) than non-parboiled rice (0.15–0.55%). A possible explanation for this could be that because parboiled rice has already been gelatinized, there is less variability due to gelatinization during cooking. This is in agreement with Raghavendra Rao and Juliano (1970), who reported that parboiled rice viscosity was less variable than that of non-parboiled rice and explained that this could be due to the homogeneity of the physical structure of parboiled rice.

3.2. Modeling of peak force and MC as a function of cooking duration

To estimate the inflection point from which the cooking duration to obtain 'well-cooked' rice could be determined, the models indicated in Table 2 were developed. Because there were no significant differences in peak force or MC values of milled rice samples with different SLCs among either the non-parboiled or parboiled rice samples, one general model for each milled rice set was developed. The parameters of Eq. (3) (s_r, s_s, b_r, b_s and d_i) are shown in Table 2 for each rice set for both peak force and MC data.

Moisture content was modeled as increasing rapidly until an inflection point, then increasing slowly thereafter for all rice sets (Fig. 7). This inflection point is speculated to indicate the end of starch gelatinization of non-parboiled rice. It is speculated that before the inflection point, starch in the endosperm gradually

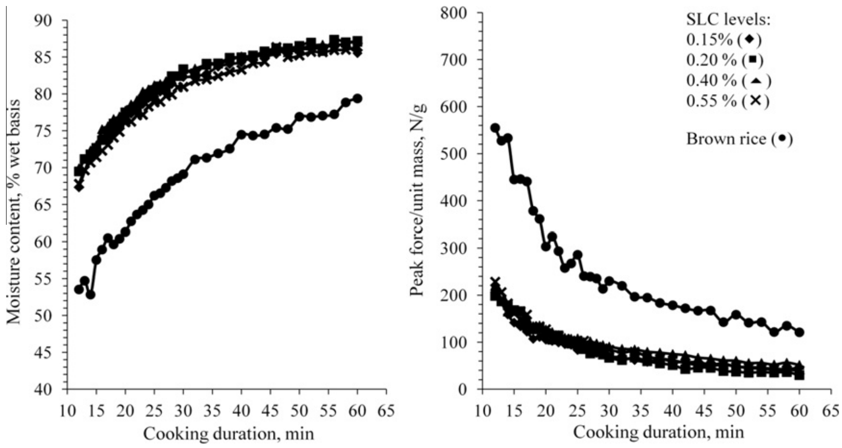

Fig. 5. Moisture content and peak force of cooked rice as a function of cooking duration for non-parboiled rice that had been milled to the indicated surface lipid content (SLC) levels.

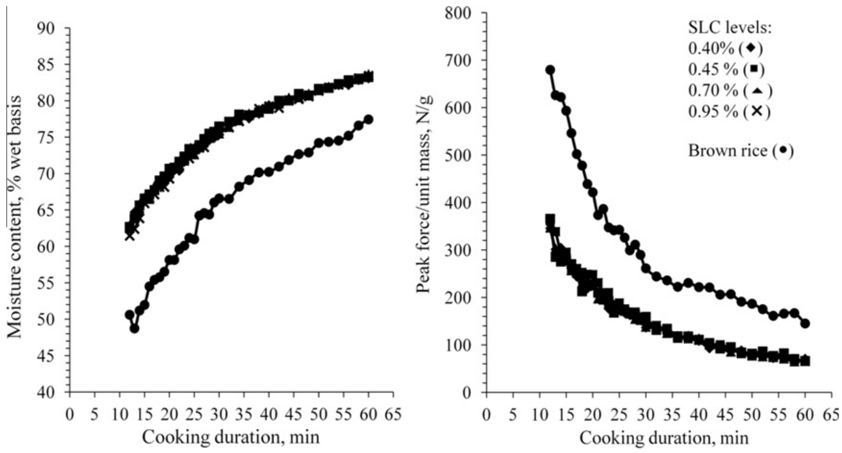

Fig. 6. Moisture content and peak force of cooked rice as a function of cooking duration for parboiled rice kernels that had been milled to the indicated surface lipid content (SLC) levels.

becomes gelatinized as moisture penetrates further into the core of the endosperm with rapid swelling. As starch gelatinizes, water is absorbed water at a faster rate and thus it is hypothesized that the "rapid" line of the model represents the cooking durations at which starch gelatinization and rapid water absorption are occurring. It is also reasoned that the starch in the core becomes gelatinized at the duration corresponding to the inflection point. After the inflection point, starch still continues to swell but at a slower rate because bran layers restrict swelling of the rice kernel. Similarly, the inflection point could indicate the full breakdown of any remaining crystalline structure in parboiled rice. Similarly, the inflection points of the peak force vs. cooking duration models of Fig. 8 could be reasoned to indicate the end of the crystalline structure of rice kernels. Thus, these inflection points were proposed as indicators of 'well-cooked' rice. Further research is needed to verify the appropriateness of this approach.

The models of Fig. 7 show that MCs of non-parboiled rice were greater than those of parboiled rice at any given cooking duration. Otegbayo and Fashakin (2001) said that the cohesive endosperm of parboiled rice, which comprises tightly-packed cells, could reduce the rate of water diffusion relative to non-parboiled rice.

Fig. 8 shows that parboiled rice was harder than non-parboiled rice at any given cooking duration. This agrees with Raghavendra Rao and Juliano (1970) and Kato et al. (1983) who found that

Table 2
Slopes, intercepts and inflection points of the models (Eqs. (1-3)) obtained using moisture content and peak force data for the indicated rice sets. GK is the cooking duration, in minutes, required to gelatinize all kernels as determined by the method of Desikachar and Subrahmanyan (1961).

Rice set	Moisture content model						Peak force model						GK
	s_r	b_r	s_s	b_s	d_i	RMSE**	s_r	b_r	s_s	b_s	d_i	RMSE	
Non-parboiled milled*	–0.8	60	–0.2	75	25	1.0	12.6	356	1.8	141	20	13	22
Non-parboiled brown	–0.9	43	–0.3	61	31	1.7	27.7	889	3.9	345	23	28	34
Parboiled milled*	–0.7	55	–0.2	69	28	0.8	12.7	478	3.2	245	25	16	–
Parboiled brown	–1.0	38	–0.3	56	29	1.2	30.6	1037	5.0	433	24	29	–

* Models were developed by pooling moisture content and peak force data obtained from all milled samples, across SLC levels.
** RMSE stands for root mean square error.

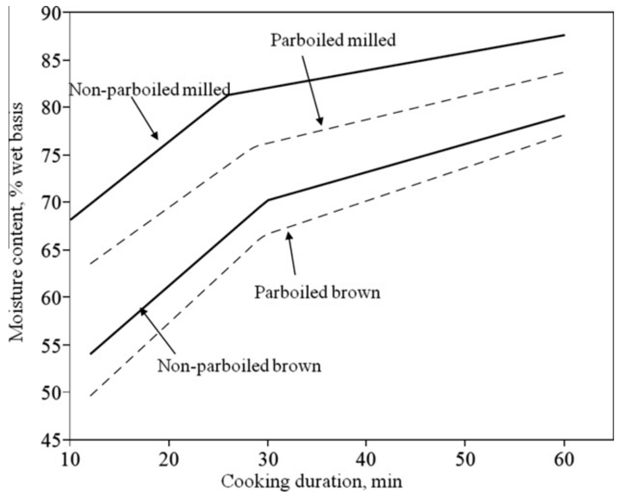

Fig. 7. Models of moisture content of cooked rice as a function of cooking duration for the indicated rice sets.

cooked parboiled rice endosperm was harder than that of cooked non-parboiled rice. Raghavendra Rao and Juliano (1970) explained that this could be due to greater adhesion/cohesion between starch and protein bodies in parboiled rice.

3.3. Cooking duration required to obtain 'well-cooked' rice (d_i)

Fig. 9 shows that there were statistical differences among methods within rice sets in determining d_i. However, for non-parboiled milled rice, d_i from the GK method (22 min) was similar, from a practical standpoint, to the d_i obtained from the MC (25 min) and peak force models (20 min). It is noted that d_i of non-parboiled brown rice obtained from the GK method (34 min) was in general agreement with the MC model (31 min), but not with the peak force model (23 min). It is speculated that the bran layers, still intact on brown rice kernels, played a role in peak force values and thus peak force would perhaps not be a good indicator of the duration required to obtain 'well-cooked' brown rice. For parboiled milled rice, d_i from the MC model (28 min) was similar, from a practical standpoint, to that from the peak force model (25 min). Finally, for parboiled brown rice, d_i from the MC model was 29 min; whereas that from the peak force model was 24 min.

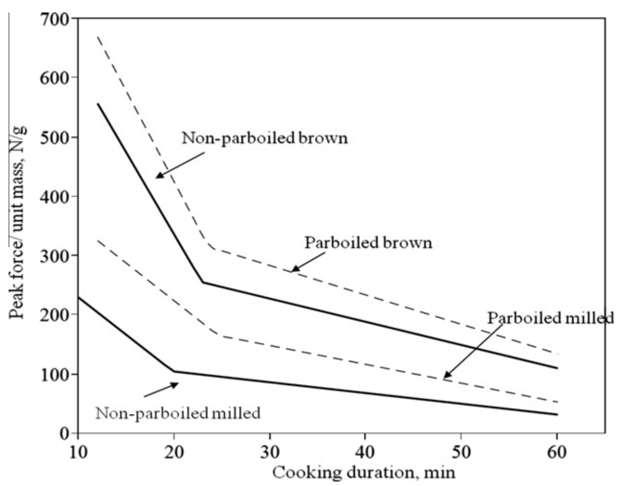

Fig. 8. Models of peak force per unit mass of cooked rice as a function of cooking duration for the indicated rice sets.

Cooking durations obtained from the MC models were always longer than those obtained from peak force models (Fig. 9). Peak force may be a more sensitive indicator of starch gelatinization than is MC and thus the drastic change in the slope that indicates d_i occurs for peak force prior to MC values. In addition, MC models showed lesser RMSE values (less variability) than peak force models, thus indicating a better appropriateness to describe cooking data (Table 2). The d_i obtained from the GK method was variable relative to the MC and peak force methods. The subjective, visual determination of the number of gelatinized kernels may explain the high variability of the GK method.

The duration to obtain 'well-cooked' non-parboiled brown rice was significantly longer than that of non-parboiled milled rice, as determined using all methods (Fig. 9). In addition, d_i of parboiled milled rice was significantly longer than for non-parboiled milled rice, as determined using all methods (Fig. 9). Sowbhagya and Ali (1991) found that the duration to achieve 72–73% MC was longer for parboiled rice than for non-parboiled rice.

Cooking durations to obtain 'well-cooked', parboiled milled and brown rice were not significantly different when using either the MC or peak force models. This suggested that cooking durations of non-parboiled rice may be more sensitive to milled rice/brown rice effects than those of parboiled rice. It is conceivable that for parboiled rice, the effect of the bran layers is less pronounced than for non-parboiled rice, and that d_i of parboiled milled rice could be taken as similar to that of parboiled brown rice. However, it is to be noted that Sowbhagya and Ali (1991) found that among parboiled samples, pressure-parboiled rice required the longest cooking duration (32.0 min), followed by normal-parboiled rice (24.0 min) and roasted-parboiled rice required the shortest cooking duration (20.5 min) to achieve 72–73% MC, suggesting that parboiling conditions affect the duration required to obtain 'well-cooked' parboiled rice. Thus, for parboiled rice, the impact of parboiling conditions on d_i could be considerable.

3.4. Sensory panel

3.4.1. Texture

Fig. 10 shows the effect of SLC and cooking duration on cooked rice hardness as determined by the sensory panel for

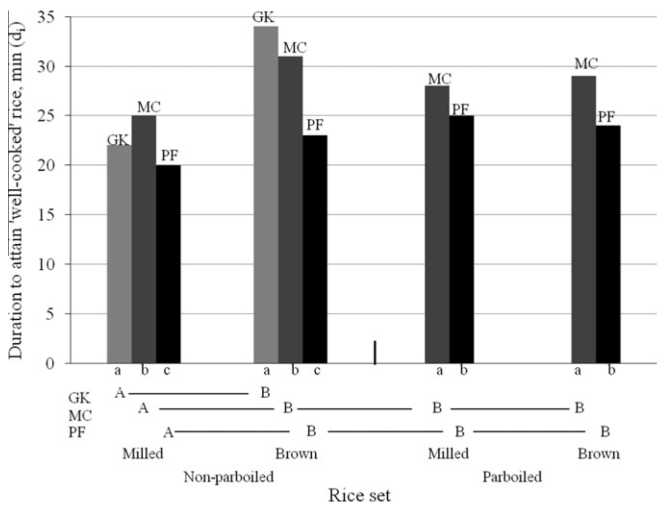

Fig. 9. Cooking durations to attain 'well-cooked' rice (d_i) obtained using the method of Desikachar and Subrahmanyan (1961) (GK), and the moisture content (MC) and peak force (PF) models (Table 2) for the rice sets indicated. Mean values of cooking duration within a rice set with different lowercase letters are significantly different ($p < 0.05$). Mean values of cooking duration obtained by the different methods across rice sets with different upper-case letters are significantly different ($p < 0.05$).

non-parboiled and parboiled milled rice. In general, non-parboiled milled samples cooked for only 16 min were significantly harder than those cooked for 18, 20 and 22 min (Fig. 10). Peak force data showed a drastic change in the slope of the peak force vs. cooking duration curve after 20 min for non-parboiled milled rice (Figs. 5 and 8). This may explain why panelists did not experience differences among samples that were cooked from 18 to 22 min. However, the GK method showed a drastic increase in the number of gelatinized kernels for the cooking duration range from 18 to 22 min for non-parboiled milled rice (Fig. 4), which was not reflected in sensory hardness scores. Parboiled rice followed similar trends as those of non-parboiled rice but was significantly harder than non-parboiled rice at any given cooking duration (Fig. 10).

In addition, there was no significant effect of SLC on sensory hardness for non-parboiled milled rice having SLCs ranging from 0.15% to 0.55% and for parboiled milled rice having SLCs ranging from 0.40% to 0.95% within any of the cooking durations tested. Similar trends were found for the number of crunchy cores, initial cohesion, toothpull and stickiness (data not shown). Thus, it is expected that consumers would not experience differences in texture if non-parboiled and parboiled rice were milled to DOM levels up to 0.55% and 0.95% SLC, respectively. However, Park et al. (2001) found that hardness of non-parboiled rice reported by a trained panel decreased significantly as DOM increased from 8% to 14% (percent bran removal).

Brown rice was significantly harder than milled rice (data not shown) for both non-parboiled and parboiled rice for the cooking durations tested, which ranged from 31 to 37 min and from 43 to 52 min, respectively (Fig. 3). These results reinforce the findings reported for peak force data (Fig. 8). In addition, sensory hardness of non-parboiled brown rice samples did not significantly vary with cooking duration, although there was an apparent decreasing trend in hardness with cooking duration. Because peak force data showed that the drastic change in slope occurred at 23 min for non-parboiled brown rice (Fig. 9), it was not expected that panelists would detect significant hardness differences within the cooking duration range of 31–37 min. The 31–37-min range was tested based on the GK method, indicating a drastic increase in the number of gelatinized kernels in this cooking duration range (Fig. 4); the cooking duration required to attain 'well-cooked' rice by the GK method was 34 min (Fig. 9; Table 2). These findings reinforce the hypothesis that other factors besides just the number of gelatinized kernels influence brown rice hardness. As with milled rice, parboiled brown rice followed similar trends as those of non-parboiled brown rice but was significantly harder than non-parboiled rice at any given cooking duration (data not shown).

3.4.2. Aroma and flavor

Milled rice flavor and aroma attributes were not significantly affected by SLC for either non-parboiled or parboiled rice having SLCs in the range of this study, suggesting that non-parboiled rice could be milled up to 0.55% SLC and parboiled rice up to 0.95% SLC without affecting cooked rice flavor (data not shown). Champagne et al. (1997) reported that intensities of corn (cooked grain), grain-starchy and water-like metallic flavors were significantly affected by DOM and that the effects of DOM were dependent on variety and location when performing regular (whiteness of 40 ± 2) and deep milling (whiteness of 49 ± 2). Park et al. (2001) found that intensities of puffed corn (cooked grain), hay-like, boiled egg white (sulfury) and wet cardboard decreased when DOM increased from 8% to 14%. In this study, only non-parboiled brown rice had significantly greater intensities of cooked grain, feedy, nutty, burlap and woody aromas and significantly lower intensities of sulfury, starchy, and metallic aromas than those of milled rice (Table 3). In addition, non-parboiled brown rice had significantly greater intensities of cooked grain, feedy, wet cardboard, nutty, burlap and woody flavors and a significantly lower intensity of sulfury flavor than those of milled rice. Parboiled brown rice had a greater intensity of burlap aroma and a lower intensity of sulfury aroma than those of parboiled milled rice (Table 3). Parboiled brown rice had greater intensities of starchy and nutty flavors than those of parboiled milled rice In addition, there was no significant effect of cooking duration on flavor attributes (data not shown).

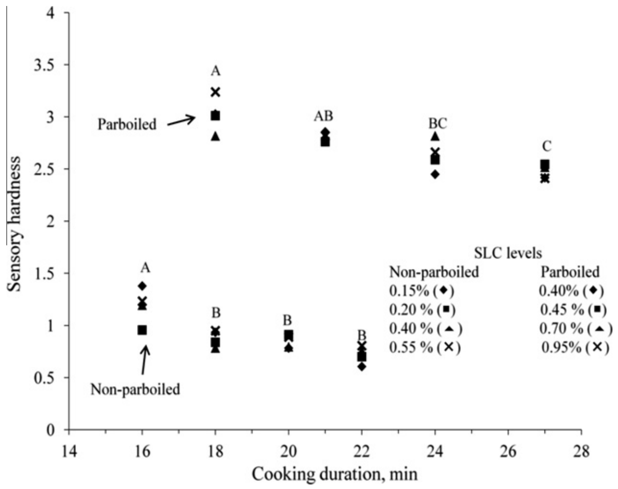

Fig. 10. Cooked rice hardness as a function of cooking duration for non-parboiled and parboiled rice milled to the indicated surface lipid content (SLC) levels. Hardness was determined by a sensory panel. Each data point indicates the mean of two replicates. For statistical analysis of the effects of cooking duration, mean values of hardness from samples at all SLCs at a given cooking duration were computed; different upper-case letters of these means across cooking duration represent significant differences.

Sweetness, sourness and saltiness were not affected by SLC for non-parboiled or parboiled rice (data not shown). However, brown rice was significantly more bitter than milled rice in both non-parboiled and parboiled rice. In addition, scorched, sweet aromatic and floral flavor attributes were not affected by SLC (including brown rice).

3.5. Cooking energy

The intention was to compare the energy required to obtain 'well-cooked' rice when cooking in excess water for the various rice sets (non-parboiled milled, non-parboiled brown, parboiled milled and parboiled brown rice). To accomplish this, a cooking duration to obtain well-cooked rice for each rice set had to be chosen, based on the evaluation method deemed most appropriate. For non-parboiled rice, this duration was obtained from the GK method because it represents a direct and somewhat standard method; the values selected were 22 min for milled and 34 min for brown rice (Table 2). For parboiled milled rice, an average duration of d_i values from the peak force and MC methods was obtained (26 min; Table 2). For parboiled brown rice, the d_i value from only the MC method (29 min; Table 2) was used because peak force was deemed to not be a good indicator of the point at which brown rice was well-cooked.

The MCs of samples within a rice set that were cooked in excess water in a rice cooker were not significantly different across the various water-to-rice ratios (3.50, 3.75 and 4.00); thus, the amount of excess water did not affect water absorption kinetics. Mean MCs of cooked rice, averaged across the three water-to-rice ratios were 75%, 69%, 72% and 63% for non-parboiled milled, non-parboiled brown, parboiled milled and parboiled brown, respectively. Bhattacharya and Sowbhagya (1971) reported that several milled, non-parboiled rice cultivars that were cooked for their optimal

Table 3
Aroma and flavor attributes for non-parboiled milled and brown rice that were cooked for 20 and 35 min, respectively; and for parboiled milled and brown rice that were cooked for 24 and 49 min, respectively.

Attribute	Non-parboiled		Parboiled	
Aroma	Milled*	Brown	Milled*	Brown
Sulfury	2.7A**	0.9B	1.7a	0.4b
Starchy	3.8A	3.4B	3.7a	3.4a
Cooked grain	3.9A	4.3B	4.3a	4.4a
Feedy	0.9A	2.0B	2.3a	1.7a
Wet Cardboard	0.5A	0.7A	0.3a	0.5a
Nutty	0.0A	0.9B	0.7a	0.8a
Burlap	1.9A	2.8B	1.5a	2.4b
Woody	0.0A	0.7B	0.8a	0.5a
Metallic	0.7A	0.0B	0.0a	0.0a
Flavor				
Sulfury	1.7A	0.3B	0.8a	0.3a
Starchy	4.1A	3.9A	3.8a	4.0b
Cooked grain	3.8A	4.3B	4.0a	4.4a
Feedy	0.0A	1.7B	2.0a	1.6a
Wet cardboad	0.4A	1.1B	0.7a	0.7a
Nutty	0.0A	0.7B	0.2a	0.7b
Burlap	0.8A	1.7B	0.8a	1.3a
Woody	0.0A	0.5B	0.3a	0.5a
Metallic	2.3A	2.4A	2.3a	2.4a

* Milled rice values for each attribute indicate the mean across SLCs ranging from 0.15% to 0.55% for non-parboiled rice and from 0.40% to 0.95% for parboiled rice.
** Mean values of attributes of non-parboiled rice with upper-case letters are significantly different ($p < 0.05$). Mean values of attributes of parboiled rice with different lowercase letters are significantly different ($p < 0.05$).

cooking duration reached a MC around 75%. Das et al. (2006) reported that a MC of 74% was necessary to obtain cooked non-parboiled rice that did not have any starchy cores. Bakalis et al. (2009) reported that cooked parboiled rice with 70% MC was accepted as fully cooked by a test panel. Sowbhagya and Ali (1991) cooked parboiled rice to 72–73% MC based on the results obtained from sensory tests. Parboiled brown rice achieved a MC of 64% for a water-to-rice ratio of 2.25, similar to the target of 63% MC used with excess water cooking to attain 'well-cooked' rice.

Fig. 11 shows the effect of water-to-rice ratio and rice set on energy requirements to cook in excess water. The bottom set of data shows the amount of energy measured to heat the water used for cooking rice from 20 to 98 °C. For a given water-to-rice ratio, this energy amount would be the same for any rice set. However, across water-to-rice ratios, this energy value would linearly increase in proportion to the increased mass of water heated. This increase in energy per water-to-rice ratio manifests itself in all of the rice set energy curves of Fig. 11.

Fig. 11 shows that the rice set that required the most energy to be cooked was non-parboiled brown, followed by parboiled brown rice, then parboiled milled and finally non-parboiled milled rice. It is noted that the hydration rates of non-parboiled milled rice with SLCs ranging from 0.15% to 0.55% were equivalent, as were those of parboiled milled rice with SLCs from 0.40% to 0.95%. Thus, the energy amounts of Fig. 11 for each of these rice sets would apply for rice over the respective SLC ranges. Because less energy would be expected to mill rice to lower degrees, this practice should lead to overall less energy use, considering both milling and cooking energy amounts. However, non-parboiled brown rice required 28% more energy to be cooked than that of non-parboiled milled rice (at a 3.5 water-to-rice ratio). Roy et al. (2008), who cooked rice using a controlled water-to-rice ratio, found that the summed energy requirements for rice processing, including dehulling, milling, and cooking, was greatest for brown rice, followed by well-milled rice and then partially-milled rice.

Fig. 11 shows that parboiled milled rice required 11% more energy to be cooked than that of non-parboiled milled rice. However,

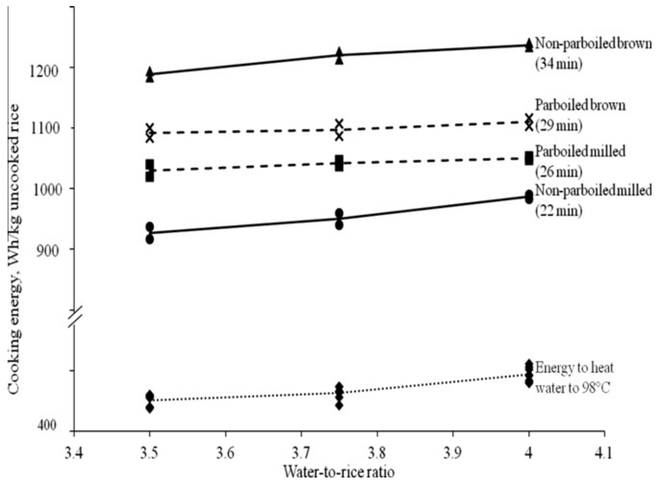

Fig. 11. Cooking energy per unit mass of uncooked rice (300 g) as a function of water-to-rice ratio for the indicated rice sets when cooking using excess water. Cooking energy is the sum of the energy required to heat water from 20 to 98 °C (dotted line) and the energy required to cook rice and water for the indicated durations (parenthesis) to attain 'well-cooked' rice. Data points indicate the cooking energy measured at the end of each cooking run using an electricity meter.

non-parboiled brown rice required more energy to be cooked than parboiled brown rice, reflecting the cooking duration data of Fig. 9. Differences in cooking energy between milled and brown rice were more pronounced for non-parboiled than parboiled rice (Fig. 11), similar to the trends observed for cooking duration (Fig. 9). For instance, for a 3.5 water-to-rice ratio, non-parboiled brown rice required 28% more energy to cook than non-parboiled milled rice, whereas parboiled brown rice required only 6% more than parboiled milled rice.

4. Conclusions

Non-parboiled rice could be milled up to 0.55% SLC and parboiled rice up to 0.95% SLC without affecting cooked rice hydration, texture, aroma, flavor and energy. However, for non-parboiled rice, brown rice required longer cooking durations and greater cooking energy to attain 'well-cooked' rice than those of milled rice. The cooking duration to attain 'well-cooked' rice of parboiled brown rice was not significantly different from that of parboiled milled rice. In addition, parboiled milled rice required longer cooking durations and greater cooking energy to attain 'well-cooked' rice than those of non-parboiled milled rice. Non-parboiled brown rice required the greatest cooking energy, followed by parboiled brown, parboiled milled and non-parboiled milled rice. It was reasoned that rice could be milled to lesser degrees without affecting cooking characteristics and eating quality.

References

Bakalis, S. et al., 2009. Modeling of rice hydration using finite elements. Journal of Food Engineering 94, 321–325.
Bhattacharya, K.R., Sowbhagya, C.M., 1971. Water uptake by rice during cooking. Cereal Science Today 16, 420–424.
Bond, N., 2004. Rice Milling. In: Champagne, E.T. (Ed.), Rice. Chemistry and Technology, 3 ed. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA, pp. 283–300.
Champagne, E.T., Wood, D.F., Juliano, B.O., Bechtel, D.B., 2004. The rice grain and its gross composition. In: Champagne, E.T. (Ed.), Rice. Chemistry and Technology, 3 ed. American Association of Cereal Chemists, Inc, St. Paul, Minnesota, U.S.A., pp. 77–107.
Champagne, E.T. et al., 1997. Effects of drying conditions, final moisture content, and degree of milling on rice flavor. Cereal Chemistry 74 (5), 566–570.
Cooper, N.T.W., Siebenmorgen, T.J., 2007. Correcting head rice yield for surface lipid content (Degree of milling) variation. Cereal Chemistry 84 (1), 88–91.

Das, T., Subramanian, A., Chakkaravarathi, A., Singh, V., Ali, S.Z., Bordoloi, P.K., 2006. Energy conservation in domestic rice cooking. Journal of Food Engineering 75, 156–166.

Desikachar, H.S.R., Raghavendra Rao, S.N., Ananthachar, T.K., 1965. Effect of degree of milling on water absorption of rice during cooking. Journal of Food Science and Technology 2, 110–112.

Desikachar, H.S.R., Subrahmanyan, V., 1961. The formation of cracks in rice during wetting and its effect on the cooking characteristics of the cereal. Cereal Chemistry 38, 356–364.

Juliano, B.O., 1985. Criteria and tests for rice grain qualities. In: Juliano, B.O. (Ed.), Rice Chemistry and Technology, second ed. American Association of Cereal Chemists, St. Paul Minnesota, pp. 443–524.

Juliano, B.O., Perez, C.M., 1983. Major factors affecting cooked milled rice hardness and cooking time. Journal of texture studies 14, 235–243.

Juliano, B.O., 1971. Relation of physicochemical properties to processing characteristics of rice. In: Proceedings of the World Cereal and Bread Congress.

Kato, H., Ohta, T., Tsuguita, T., Hosaka, Y., 1983. Effect of parboiling on texture and flavour components of cooked rice. Journal of Agricultural and Food Chemistry 31, 818–823.

Lanning, S.B., Siebenmorgen, T.J., 2011. Comparison of milling characteristics of hybrid and pureline rice cultivars. Applied Engineering in Agriculture 27 (5), 787–795.

Lucisano, M., Mariotti, M., Pagani, M.A., Bottega, G., Fongaro, L., 2009. Cooking and textural properties of some traditional and aromatic rice cultivars. Cereal Chemistry 86 (5), 542–548.

Meilgaard, M., Civille, G.V., Carr, B.T., 1999. Sensory Evaluation Techniques, third ed. CRC Press Inc., Boca Raton, Florida, USA, p. 387.

Mohapatra, D., Bal, S., 2006. Cooking quality and instrumental textural attributes of cooked rice for different milling fractions. Journal of Food Engineering 73 (3), 253–259.

Ondier, G.O., Siebenmorgen, T.J., Mauromoustakos, A., tul=0?>Ondier et al., accepted for publication. Equilibrium moisture contents of pureline, hybrid, and parboiled rice kernel fractions. Transactions of ASABE.

Otegbayo, B.O.O.F., Fashakin, J.B., 2001. Effect of parboiling on physico-chemical qualities of two local rice varieties in Nigeria. The Journal of Food Technology in Africa 6 (4), 130–132.

Park, J.K., Kim, S.S., Kim, K.O., 2001. Effect of milling ratio on sensory properties of cooked rice and on physicochemical properties of milled cooked rice. Cereal Chemistry 78 (2), 151–156.

Perdon, A.A., Siebenmorgen, T.J., Mauromoustakos, A., Griffin, V.K., Jhonson, E.R., 2001. Degree of milling effects on rice pasting properties. Cereal Chemistry 78 (2), 205–209.

Raghavendra Rao, S.N., Juliano, B.O., 1970. Effect of parboiling on some physicochemical properties of rice. Journal of Agricultural and Food Chemistry 18 (2), 289–294.

Ranghino, F., 1966. Valutazione della resistenza del riso alla cottura, in base al tempo de gelatinizzazione del granelli. Riso 15, 117–127.

Roy, P., Ijiri, T., Okadome, H., Nei, D., Orikasa, T., Nakamura, N., et al., 2008. Effect of processing conditions on overall energy consumption and quality of rice (*Oryza sativa* L.). Journal of Food Engineering 89 (3), 343–348.

Roy, P., Shimizu, N., Kimura, T., 2004. Energy conservation in cooking of milled raw and parboiled rice. Food Science and Technology Research 10 (2), 121–126.

Saleh, M.I., Meullenet, J., 2007. Effect of moisture content at harvest and degree of milling (based on surface lipid content) on the texture properties of cooked long-grain rice. Cereal Chemistry 84 (2), 119–124.

Sowbhagya, C.M., Ali, S.Z., 1991. Effect of presoaking on cooking time and texture of raw and parboiled rice. Journal of Food Science and Technology 28 (2), 76–80.

Suwansri, S., Meullenet, J.-F., Hankins, J.A., Griffin, K., 2002. Preference mapping of domestic/imported jasmin rice for U.S.-Asian consumers. Journal of Food Science 67 (6), 2420–2431.