DESIGN AND PROCESSING PERFORMANCE OF A PILOT-SCALE PARBOILING UNIT

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ABSTRACT. *A partially-automated parboiling unit (PU) that can process approximately 2 kg of rough rice per cycle was recently developed and is described. The system components include a stainless steel tank (40-cm long; 20-cm internal diameter), a water-circulation pump, a hot-water supply tank, a steam regulator, four cylindrical sample containers, and a computer interface. The processing performance of the PU was evaluated using rough rice of the long-grain cultivar CL151 obtained from two growing locations. Sample size and location of the sample containers in the tank were the variables considered in the performance tests. The processing conditions were: soaking at 70°C and 138 kPa$_g$ (20 psi$_g$) for 2 h; steaming at 120°C and 69 kPa$_g$ (10 psi$_g$) for 10 min; and gentle drying at 26°C and 65% relative humidity until a moisture content of ~12% was attained. The quality attributes of the parboiled product were compared with those obtained by a laboratory-scale parboiling procedure that employed autoclave steaming. Differences in the percentage of deformed kernels were observed due to the effect of sample size and location of the sample containers in the tank. Milling yields and milled kernel color were minimally affected. In general, the quality attributes of parboiled rice obtained by the PU were either similar or better than those of the product obtained by autoclave steaming. Automated process operations (soaking, draining, and steaming), small sample size requirements, and good reproducibility are some key features that make the PU a valuable tool for rice parboiling and general processing research.*

Keywords. Rice, Parboiling, Autoclave steaming, Milling quality.

Parboiling rice involves a series of unit operations, the primary of which are soaking, steaming, and drying. The success or performance of a parboiling system is typically measured by the quality of the parboiled rice produced; several criteria can be used in this assessment. Milling yield quantifies the edible amount of rice endosperm produced by milling operations and is expressed in terms of both the milled rice yield (MRY) and head rice yield (HRY). Milled rice yield is calculated as the mass fraction of dried, rough rice that remains as milled rice, to include both broken and head rice kernels, once the hulls and a desired level of the bran have been removed (USDA, 2009). USDA (2009) defines head rice as milled kernels that "are at least three-fourths the length of an unbroken kernel." Once brokens are removed from milled rice, HRY is calculated by dividing the head rice mass by the original rough rice mass. Both MRY and HRY are generally expressed as a percentage (USDA, 2009).

Maximizing HRY is a priority of rice processors since broken kernels are typically worth approximately 60% or less the value of head rice (Siebenmorgen et al., 2007).

Rough rice kernels with fissures in the endosperm generally break apart during milling, producing broken kernels (Cnossen and Siebenmorgen, 2000; Iguaz et al., 2006; Siebenmorgen et al., 2007). Parboiling mends fissures through the gelatinization of rice starch during steaming, thus improving milling yields (Bhattacharya and Rao, 1966; Bhattacharya 1985; Islam et al., 2002); this is one of the primary benefits of the process.

In addition to milling yield, parboiled rice quality is characterized by milled kernel color. Parboiling conditions influence rice color parameters as indicated by Bhattacharya and Rao (1966) and Bhattacharya (1985), who showed that milled rice yellowness increased, whereas whiteness decreased, under high parboiling temperatures.

Factors during rice production can affect physicochemical properties and resultant processing behavior. Most notably, nighttime air temperatures during critical reproductive stages have been correlated to chalk levels and milling yields (Cooper et al., 2006; Cooper et al., 2008; Ambardekar et al., 2011; Lanning et al., 2011), functional properties such as amylose content, gelatinization temperature, and paste viscosity (Lisle et al., 2000; Dang and Copeland 2004; Cooper et al., 2008; Lanning et al., 2012), and milled rice endosperm color (Lanning and Siebenmorgen 2013). The correlation of kernel properties to environmental temperatures during kernel formation implies that rice processing characteristics may vary by production location and by year. Additionally, processing properties often vary due to genetic differences among cultivars (Bhattacharya and Rao 1966; Bhattacharya 1985; Biswas and Juliano 1988).

Whether due to production factors or genetic differences, variability in processing behavior often exists, and thus end-use processing systems, including parboiling operations, must be routinely adjusted to account for changes in properties. The type and amount of adjustment in industrial-scale parboiling settings to account for these variable properties is often not known. A small-scale parboiling unit (PU) would be useful in estimating optimal, commercial-scale parboiling conditions for various rice lots. Furthermore, such a unit would be useful in research efforts to characterize the impacts of cultivars and production factors on parboiling performance. At present, no small-scale PUs are commercially available, hence, a prototype unit was developed. The objectives herein are to develop a PU prototype, investigate its control capabilities, and evaluate the sources of parboiling performance variability within the system.

MATERIALS AND METHODS

PARBOILING UNIT DESIGN

The PU comprises a horizontally-oriented, 20.0-cm (7.9-in.) internal diameter, 40.0-cm (15.7-in.) long, 304 stainless steel tank (figs. 1a and 1b), designed to withstand pressures up to 689 kPa_g (100 psi_g). The tank opens on the front-facing flat end with a swing-bolt-hinged closure that seals via a 6.5-mm diameter o-ring. Seventeen, National Pipe Thread (NPT) ports are positioned on the top, bottom, sides, and back of the tank. Six of these ports are plumbed with 1.3-cm (0.5-in.) fittings for introduction and exhaust of air, steam, and water. A pressure sensor (fig. 1b: G) and the main pressure gauge (fig. 1b: H) are plumbed into 0.64-cm (0.25-in.) ports. Three optical, liquid-level sensors (fig. 1b: E1-3) indicate water level in the tank; these sen-

sors are plumbed into 1.3-cm (0.5-in.) ports spaced equally from the bottom to the top of the tank. A pressure relief valve (fig. 1b: N), set to release at 689 kPa_g (100 psi_g), is plumbed into a 2.54-cm (1-in.) port. Four thermocouple probes are plumbed into 0.6-cm (0.25-in.) ports (fig. 1b: F1-4). An immersion heater (fig. 1b: A), with a diameter of 1.8 cm (0.72 in.) and enclosed within a 316 stainless steel sheath, is plumbed into a 3.2-cm (1.25-in.) port on the back, flat side of the tank. A steam regulator (fig. 1b: K), capable of maintaining steam pressure from 21 to 103 kPa_g (3 to 15 psi_g), and a water pressure regulator (fig. 1b: L), capable of maintaining water pressure from 172 to 517 kPa_g (25 to 75 psi_g), are plumbed into 1.5-cm (0.5-in.) ports at the top of the PU. Safety mechanisms include manually-controlled ball valves (fig. 1b: D1-2) positioned to rapidly close off water and steam flow, a pressure relief valve, an emergency button (fig. 1b: P) that disconnects electrical power to the PU, two 10-amp circuit breakers for the heater and solenoid valves, respectively, and a tank pressure gauge (fig. 1b: H).

The sample containers of the unit comprise four cylinders (32.0 cm long; 7.4 cm diameter) constructed of round-hole, 304 stainless steel perforated sheet (0.95-mm thickness; 1.59-mm hole diameter; and 2.38-mm center spacing between holes). The container lids (7.6-cm diameter; 2.2-cm high), also made of the same material, are fitted to the containers with a hose clamp. The cylindrical containers are positioned in the tank by a removable metal manifold. Each container has a capacity of 480 g of rough rice at 12% MC (MCs are expressed on a wet basis) and rough rice bulk density of 552 kg/m^3. This sample mass limit provides sufficient headspace for the expansion of kernels during soaking and steaming. Hence, the maximum processing capacity
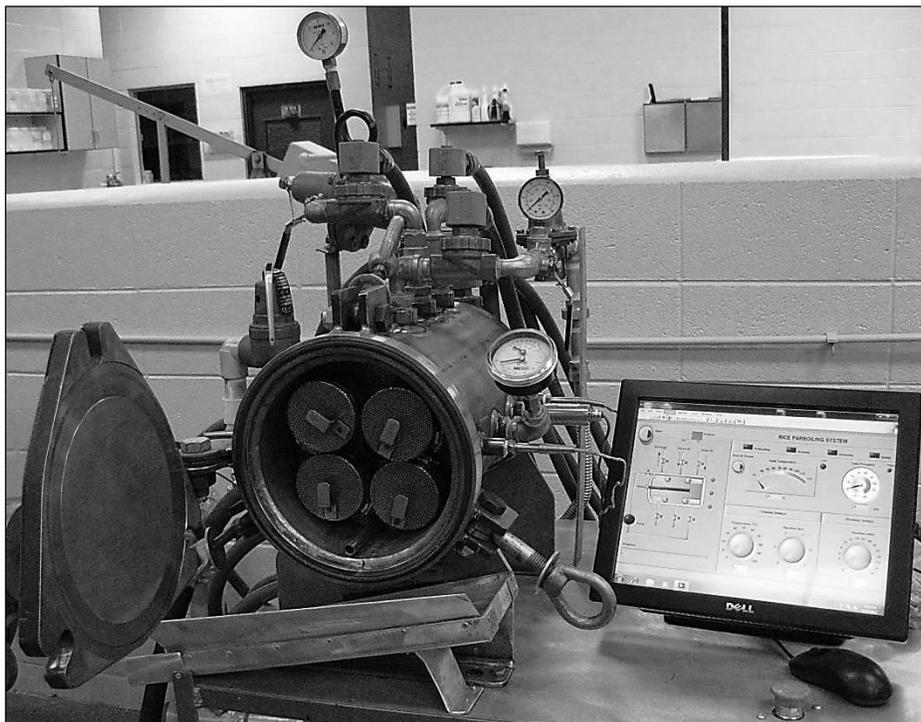
Figure 1a. A photograph showing the parboiling unit tank, sample containers, and computer control panel.

ELEVATION VIEW **RIGHT END VIEW**

TOP (PLAN VIEW)

ITEM	NAME	BRAND	MODEL	SPECIFICATION
A	Screw-plug heater	Omega	EMH-110-120V	11/4" NPT, 11" length, 1000 W, 24 W/in2
B1-7	Solenoid valve	Asco	8220-G404	1/2" NTP, 120V/60Hz, Hot Water/Steam
C	Circulation pump	Grundfos	UPS15-58FC	1" NPT, 3-Speed, 1/25 HP, 115V
D1-4	Ball valve	Apollo	76-103-01	1/2" NPT, Two Piece, 316 SS Body
E1-3	Level sensor	SDM	OS-150A-05	1/2" NPT, 5 VDC, Wet, T.max. 125 C
F1-4	Thermocouple probe	Omega	TC-J-NPT-U-72	1/4" NPT, Type J, Ungrounded
G	Pressure sensor	Omega	PX209-30V85G10V	1/4" NPT, 0-10V, -14.7 to 85 PSI
H	Main gauge	Weiss	CTP25R	1/4" NPT, 0 to 75 PSI, 60 to 260 F
I	Steam pressure gauge	Trerice	52-2709	1/4" NPT, 0 to 30 PSI
J	Water pressure gauge		4FLU1	1/4" NPT, 0 to 100 PSI
K	Steam pressure regulator	Spence	15271	1/2" FNPT, Pressure regulation 3 to 15 PSI
L	Water pressure reducer	Watts	1/2-25-AUB GG	1/2" FNPT, Pressure regulation 25 to 75 PSI
M	Check valve	Apollo	62-103-01	1/2" FNPT, Cracking pressure 0.5 PSI
N	Relief valve	Watts	1-174A-100	1" FNPT, Bronze, Preset setting 100 PSI
O	Tank with water heater	Stiebel Eltron	SHC 4	1/2" NPT, 74 to 165 F, 1200 W, 110V
P	Emergency button	Schneider Electric	XB4BS542	40 mm Emergency stop mushroom head
Q	Flow meter	Omega	FL-9010	1" NTP, 1 to 10 GPM
R	Display	Dell	E157FPT	15", Touch-screen, Flat panel monitor
S	Computer	Dell	OptiPlex 580	

Figure 1b. Pilot-scale parboiling unit design schematics and parts descriptions.

of the PU is four, 480-g individual samples, or a total of 1,920 g per cycle.

The soaking temperature capabilities of the PU system are 20°C to 95°C (104°F to 203°F) and the water pressure capabilities are 103 to 517 kPa$_g$ (15 to 75 psi$_g$). The steaming pressure capabilities are 0 to 103 kPa$_g$ (0 to 15 psig). Computer software (LabView, National Instruments Corpo-ration, Austin, Tex.) was used to design a user-interactive control panel to monitor processing functions and to develop visual representation of the data and processes occurring during the parboiling process. Via the control panel, the soaking temperature and duration, as well as the steaming temperature/pressure and duration are set before parboiling begins.

PARBOILING UNIT OPERATION

A step for preheating the PU was designed to help ensure uniform initial conditions from one parboiling cycle to another. Preheating is accomplished by passing steam through the PU tank prior to inserting rice samples. The steam ball valve at the top of the PU (fig. 1b: D2) is first opened manually to allow steam flow to the steam solenoid valve (fig.1b: B2). Preheating is initiated by engaging the indicated "preheat switch" on the control panel. The steam solenoid valves located above (fig. 1b: B2) and below (fig. 1b: B6) the tank are then automatically opened, allowing steam to flow through the tank. After preheating for 3 min, the steam solenoid valves close, and the parboiling cycle is ready to begin.

Prior to the soaking step, water is heated using a conventional hot-water tank (fig. 1b: O), capable of heating to 90°C. The desired water pressure to be used during soaking is set manually using a water pressure regulator (fig. 1b: L). Soaking and steaming conditions and durations are set on the control panel prior to the soaking step. Once samples are inserted into the tank and the tank door is sealed, the soaking process is initiated by pressing a "start" option on the control panel (fig. 1b: R). The water and air solenoid valves (fig. 1b: B1, B3) at the top of the PU automatically open, allowing water from the hot-water tank to fill the PU tank and displaced air to be vented. When the PU tank is full of water, as indicated by the water level sensors, the water and air vent solenoid valves automatically close, and in-line water solenoid valves (fig. 1b: B4, B5) automatically open to allow circulation of water throughout the PU tank. A pump (fig. 1b: C) at the bottom of the tank circulates the soaking water at a rate of 11.4 L/min (3 gal/min) which is indicated by a flow meter (fig. 1b: Q). The immersion heater is activated when the average soaking water temperature, as measured by the four tank thermocouples, is 2°C less than the specified soaking temperature entered via the control panel, and deactivated when the average temperature is 1°C greater than the specified soaking temperature. If the soaking water temperature decreases to 5°C less than the setpoint, a "heat with steam" option is used to more rapidly increase soaking water temperature to desired levels. Manually activating this option causes the steam and air-vent solenoid valves (fig. 1b: B2, B3) to open and allows steam to heat the water. The "heat with steam" process is deactivated manually when the soaking water reaches the specified soaking temperature. When the soaking duration has elapsed, as indicated by a green progression bar on the control panel, the water pump ceases to circulate soaking water, and the water solenoid valve (fig. 1b: B7) at the bottom of the PU opens, draining the water. The steam solenoid valve (fig. 1b: B2) at the top of the PU opens automatically for 2 min, providing steam pressure/flow to help remove the soaking water.

Once the 2-min draining interval is complete, the water solenoid valve (fig. 1b: B7) closes and the steam solenoid valves (fig. 1b: B2, B6) at the top and bottom of the PU open, allowing steam to flow through the PU tank. After the specified steaming duration, the steam solenoid valves automatically close to terminate steam access to the tank. The air solenoid valve (fig. 1b: B3) then opens, allowing air to enter and steam to vent the PU tank (D4). After 1 min, the samples are removed for drying.

During the soaking and steaming durations, temperature readings from the four thermocouples, pressure readings from the pressure sensor, and water level readings from the three liquid-level sensors are recorded via the PU software every 5 s. This data is subsequently checked to ensure that the desired temperature and pressure settings were maintained throughout the parboiling operations.

RICE SAMPLES

Rough rice lots of the pureline, long-grain cultivar, CL151, were obtained in 2011 from two locations in Arkansas: one from Harrisburg (CL151-H), and another from Weona (CL151-W). CL151-H and CL151-W were harvested at 15.2% and 17.0% MC, respectively. Initial HRY and percent chalk data indicated that CL151-H and CL151-W were mediocre- and good-quality rice, respectively. CL151-W had a greater HRY (66.1% vs. 51.5%) and a lesser percent chalk (4.3% vs. 8.9%) than CL151-H. The lots were cleaned (Carter-Day Dockage Tester, Carter-Day Co., Minneapolis, Minn.), sealed in plastic containers, and stored at 4°C. Before parboiling, samples were dried on meshed trays (40×30 cm) in a chamber with air conditions held at 26°C and 65% relative humidity by a temperature and relative humidity controller (AA5582, Parameter Generation and Control, Inc., Black Mountain, N.C.) until the samples attained ~12.0% MC. Moisture contents were measured by drying duplicate, 10-g samples in a convection oven for 24 h at 130°C (Jindal and Siebenmorgen, 1987).

PERFORMANCE TESTING

Two main variables were considered in evaluating the performance of the PU: (1) location of the four sample containers inside the tank, and (2) sample size (i.e. mass of rough rice loaded in each container). The lot from Weona, Arkansas, (CL151-W) was used in examining the effect of sample container location. Each cylinder (designated as cylinders 1, 2, 3, and 4 in fig. 2) was filled with 320 g of rough rice. The parboiling process comprised soaking the rough rice for 2 h at 70°C with a water pressure of 138 kPa_g (20 psi_g); followed by steaming for 10 min at 116-120°C and a pressure of 69 kPa_g (10 psi_g); and then gently drying at 26°C and 65% relative humidity as described earlier. These conditions were based on parboiling procedures reported in previous works (Bhattacharya and Rao 1966; Biswas and Juliano 1988; Patindol et al., 2008). For comparison, a 320-g rough rice sample was parboiled by a laboratory procedure using a water bath (SL-1235, Sheldon Manufacturing Inc., Cornelius, Ore.) for soaking, an autoclave-steam sterilizer (Brinkmann 2340E, Tuttnauer USA Co. Ltd., Hauppauge, N.Y.) for steaming, and adopting the same soaking and steaming conditions (temperature, pressure, and duration) as the PU. Tests were conducted in duplicate.
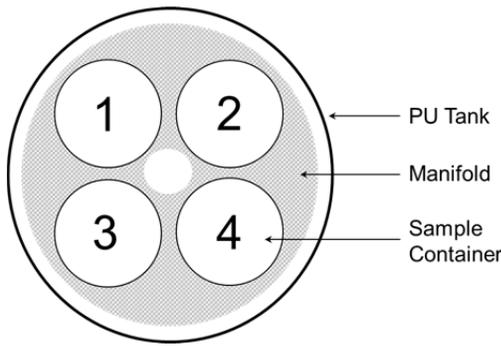
Figure 2. Location of the four cylindrical sample containers inside the tank of the parboiling unit; with cylinders 1 and 2 (C1 and C2) on the upper section of the PU tank, and cylinders 3 and 4 (C1 and C4) on the bottom.

The effect of sample size was investigated by performing three parboiling cycles each for samples CL151-H and CL151-W. The three cycles involved loading each of the four sample containers with 170, 320, or 470 g of rough rice. These quantities were selected in relation to the sample mass requirement for a milling test, which is 150 g of rough rice. Hence, the three cycles were enough for one, two, or three 150-g milling measurements, respectively, for every cylindrical container. Samples were parboiled using the same conditions for soaking, steaming, and drying as described earlier and the tests were also duplicated.

PARBOILED RICE EVALUATION

Milling yield analyses were performed by first dehulling duplicate, 150-g rough rice samples using a laboratory sheller (THU-35A, Satake Engineering Co., Ltd., Tokyo, Japan) with

a roller clearance of 0.048 cm. The resulting brown rice was then milled for 75 s in a laboratory mill (McGill Miller #2, Rapsco, Brookshire, Tex.). The milling duration was chosen based on a degree of milling curve (fig. 3) established according to Lanning and Siebenmorgen (2011). A two-screen sizing device (Grain Machinery Mfg., Miami, Fla.) was used to separate broken kernels from head rice. Head rice samples were aspirated for 2 min to remove residual bran particles using an aspirator (Seedburo Equipment Company, Chicago, Ill.). Duplicate, 50-g head rice samples were used in quantifying the percentage of deformed kernels. These included kernels that were at least three-fourths their original length but were either bent, flattened, jagged, wrinkled, tapered, or elongated due to the parboiling treatment (fig. 4). Deformed kernels were separated by visual inspection and expressed as a mass percentage of the 50-g head rice sample. Head rice color was measured
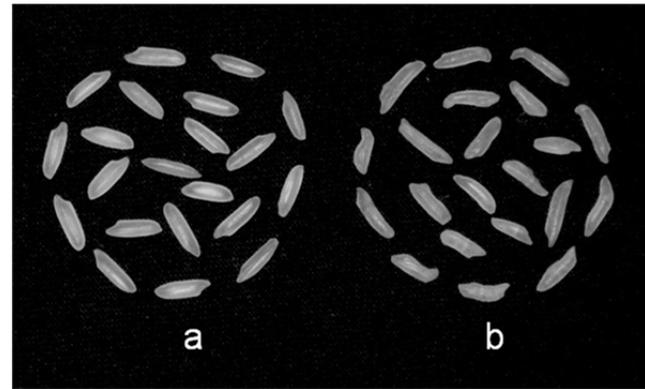
Figure 4. Normal (a) and deformed (b) milled rice kernels obtained after milling of dried, parboiled rough rice.
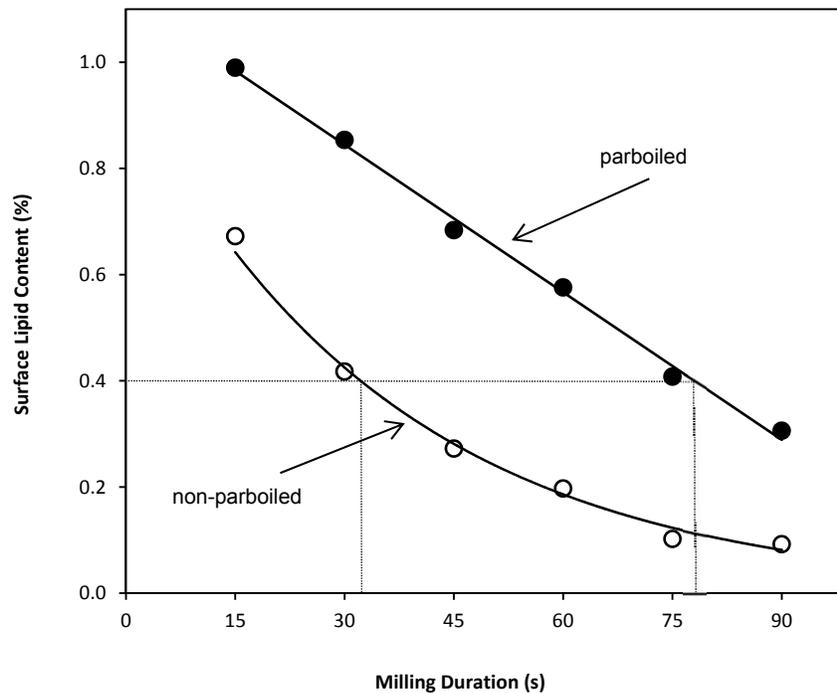
Figure 3. Degree of milling curves for parboiled and non-parboiled long-grain rice, CL151 (with each data point as a mean from duplicate measurements of two replicated tests).

by the L*a*b* color space principle using a colorimeter (ColorFlex, Hunter Associates Laboratory, Reston, Va.). Briefly, a clear, flat-bottom dish was filled with approximately 30 g of head rice, placed at the center of the sample port, and covered. After taking the first measurement, the sample cup was rotated 90°, and a second measurement was performed. The L*a*b* values were taken as an average of the two readings for each sample. L* (lightness) and b* (yellowness) are the parameters with significance to parboiled milled rice. Surface lipid content was determined using a lipid extraction system (Soxtec Avanti 2055, Foss North America, Eden Prairie, Minn.) according to AACC method 30-20 (AACC International, 2000), with modifications by Matsler and Siebenmorgen (2005). Surface lipid content was expressed as the mass percentage of extracted lipid to the original head rice. Chalk measurements were performed on duplicate, 100-kernel brown rice samples using an image analysis system (WinSeedle Pro 2005aTM, Regent Instruments, Sainte-Foy, Quebec, Canada) as described by Ambardekar et al. (2011). Percent chalk was calculated as the ratio of the total chalky area (pixels) of the 100-kernel set to the total area of the kernels, multiplied by 100.

STATISTICAL ANALYSES

Statistical analyses were carried out using JMP® software version 9 (SAS Institute, Cary, N.C.). Analysis of variance at α=0.05 was used to evaluate the effects of sample location and size on parboiled rice properties. Tukey's HSD (honestly significant difference) test was used to identify significant differences among treatment means. For the sample location test, the experiment was completely randomized with cylinder location as the source of variation. For the sample size test, the experiment was laid out as 5×2 factorial with sample size and sample lot as main sources of variation. Non-parboiled and autoclaved samples were used as controls.

RESULTS AND DISCUSSION

Parboiling condition variability may be evaluated by analyzing the temperature and pressure measurements recorded throughout the course of soaking and steaming (fig 5). Figure 5a shows that the temperature readings throughout the course of a parboiling cycle were very stable. However, some occasional spikes were observed on the soaking-water pressure readings (fig. 5b). Such spikes may be at-
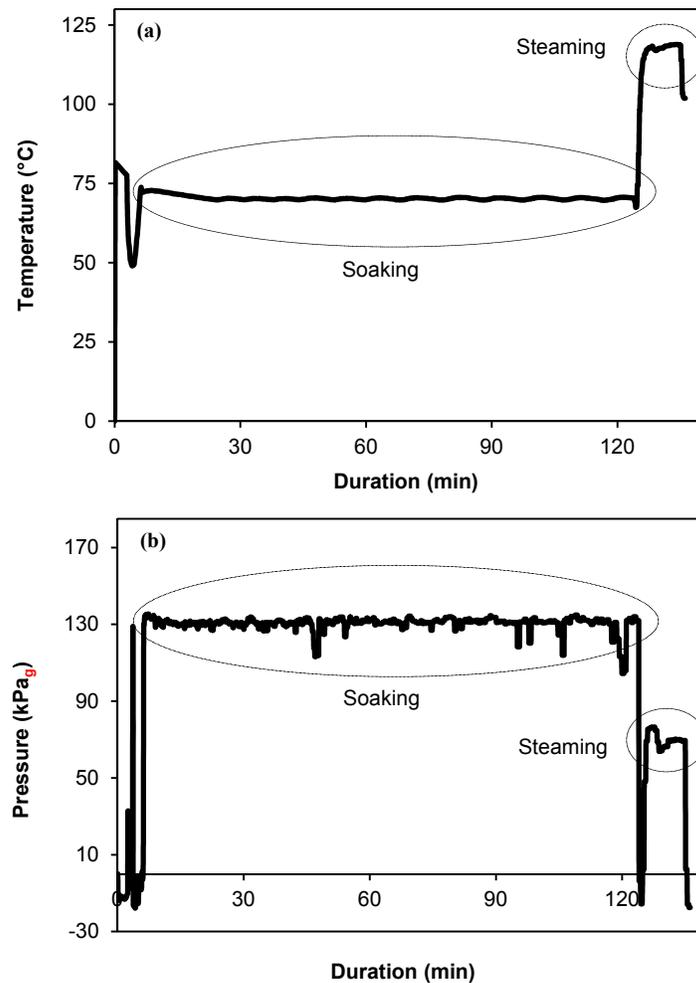
Figure 5. Temperature (a) and pressure (b) measurements for a parboiling cycle that comprised soaking at 70°C and 138 kPa$_g$ for 2 h and steaming at 120°C and 69 kPa$_g$ for 10 min.

tributed not to the PU itself but the pressure of the external water source, which is the municipal water system. Essentially, the PU performance satisfies the objective of maintaining temperature and pressure settings reasonably accurate.

MILLABILITY OF PARBOILED RICE

Kernels of parboiled rice harden after drying (Bhattacharya and Rao 1966; Rao and Juliano 1970; Bhattacharya 1985; Biswas and Juliano 1988), making bran removal during milling more difficult. Figure 3 shows degree of milling curves (millability) for parboiled and non-parboiled CL151-W established according to the procedure of Lanning and Siebenmorgen (2011). In these curves, head rice surface lipid content (SLC) is plotted against milling duration. For the particular set of milling durations used in this work (15, 30, 45, 60, 75, and 90 s), the data for the non-parboiled sample were described by an exponential equation ($y=0.9707e^{-0.028x}$; $R^2=0.982$), which is in agreement with the trends of Lanning and Siebenmorgen (2011). In contrast, the parboiled sample data points fit a linear pattern ($y=-0.0093x+1.123$; $R^2=0.996$). This different pattern may be attributed to the inward diffusion of some bran components, including lipids, to the endosperm during parboiling (Rao and Juliano, 1970; Bhattacharya, 1985). Non-parboiled rice is typically milled to an SLC of 0.3-0.5% (Siebenmorgen and Sun, 1994; Matsler and Siebenmorgen, 2005; Lanning and Siebenmorgen, 2011). The degree of milling curves show that to attain an SLC target of 0.4%, approximately 30 and 75 s were required to mill the non-parboiled and parboiled samples, respectively. Consequently, all parboiled samples (processed using the PU and autoclave) were milled for a duration of 75 s.

EFFECT OF SAMPLE CONTAINER LOCATION

Visual inspection of parboiled rough rice samples right out of the PU indicated that bursting, which is characterized by splitting of hulls due to extensive kernel expansion and leaching of some endosperm components (Bhattacharya and Rao 1966; Islam et al., 2002), was most evident on the samples placed in cylinder 1 (C1), followed by the samples in cylinder 2 (C2), and then those in cylinders 3 and 4 (C3 and C4). Visually, the extent of bursting was in the order, C1>C2>C3=C4. Literature emphasizes that the MC of parboiled rough rice is typically around 35% (Bhattacharya, 1985); a greater value may imply that bursting and extensive starch gelatinization may have ensued (Bhattacharya and Rao, 1966; Bhattacharya, 1985; Islam et al., 2002). As

shown in table 1, the MC of freshly-parboiled samples from the PU exceeded 35%, and was greatest for the sample loaded in C1, followed by that in C2, and then those in C3 and C4 (C1>C2>C3=C4). This trend in MC completely agreed with the visual observations of the extent of rough rice bursting. Bursting is unfavorable as it contributes to deformed kernels (fig. 4) upon subsequent drying and milling (Bhattacharya and Rao, 1966; Bhattacharya, 1985), as well as milling yield reduction (Islam et al., 2002). The trend in percentage of deformed kernels was identical to that of the MC (C1>C2>C3=C4). Deformed kernels impart a negative impact on the visual quality of milled parboiled rice. Upon sorting on the sizing device, the deformed kernels blended into the head rice bulk because their length was similar to that of the normal head rice.

MRY did not differ among the four cylinders (data not shown). However, HRY was greater for the samples loaded in C3 and C4 than in C1 and C2 (table 1). For color parameters (L* and b* values), the effect of location of the sample containers in the tank was statistically insignificant. Variations in sample MC, HRY, and percentage of deformed kernels are indicative of skewed exposure to the temperature-pressure treatment. The C1 and C2 containers were positioned on the upper section of the tank, whereas the C3 and C4 containers were positioned at the bottom (fig. 2). Hot water and steam were introduced through inlets at the top of the PU tank (fig. 1:B2, B3). This design may initially expose the samples in positions C1 and C2 to hot water and/or steam with greater temperatures for greater durations than those in the C3 and C4 locations, and consequently affect the rate of heat transfer, water absorption, and gelatinization of rice starchy endosperm.

The rice samples parboiled by autoclave steaming had lesser MC than the PU counterparts (table 1). Moisture may have been lost in transit from soaking, to draining, and to steaming, as these process operations were carried out in three separate pieces of equipment. Despite the lesser MC, the autoclaved samples were comparable to the PU samples in milling yields (C3 and C4 positions) and percentage deformed kernels (C2). However, the milled parboiled rice obtained by autoclave steaming was noticeably darker than the PU counterparts; this visual observation is supported by relatively low L* (lightness) and high b* (yellowness) readings (table 1). Steaming with a laboratory autoclave required 9-12 min to attain the steam temperature and pressure setpoints as opposed to the PU that required less than 3 min (fig. 5). The longer transition time may have caused the darker color of the autoclaved samples as previous stud-

Table 1. Effect of sample container location inside the tank of the PU (as described in fig. 2) on the properties of CL151-W (Weona lot) parboiled rice[a], [b].

Sample/ Container Location	Moisture Content[c] (%)	Deformed Kernels (%)	Head Rice Yield (%)	L* (lightness)	b* (yellowness)
1	41.8 ± 1.2[a]	32.1 ± 0.8[a]	66.4 ± 0.8[b]	53.3 ± 0.8[ab]	24.7 ± 0.6[b]
2	39.9 ± 1.2[b]	25.5 ± 1.3[b]	67.9 ± 0.8[b]	54.0 ± 0.7[a]	24.4 ± 0.6[b]
3	36.6 ± 0.7[c]	16.8 ± 2.1[c]	70.8 ± 0.6[a]	54.1 ± 1.1[a]	24.0 ± 0.5[b]
4	36.0 ± 1.0[c]	16.6 ± 1.2[c]	70.5 ± 1.1[a]	54.5 ± 1.3[a]	23.5 ± 0.4[b]
Autoclaved[d]	33.2 ± 1.0[d]	25.9 ± 1.1[b]	70.9 ± 1.5[a]	52.9 ± 1.3[b]	26.2 ± 0.4[a]

[a] Values are means from duplicate measurements of two replicate tests ± standard deviations.
[b] Means in a column followed by a common superscript letter(s) are not significantly different at *P* <0.05 based on Tukey's HSD test.
[c] Rough rice moisture content (wet basis) immediately after parboiling.
[d] Sample parboiled by autoclave steaming.

ies (Bhattacharya and Rao 1966; Bhattacharya 1985; Islam et al., 2002) have indicated that longer steam exposure increases kernel yellowness and decreases whiteness.

EFFECT OF SAMPLE SIZE

Similar trends were observed on the effect of sample size on parboiled rice properties, regardless of the position of the containers (C1, C2, C3, or C4) in the PU tank. For ease of discussion, only the data collected from the container positioned in C3 is presented in table 2. The table shows the properties of CL151-H (Harrisburg) and CL151-W (Weona) lots parboiled with various sample sizes (170, 320, and 470 g) using the soaking and steaming conditions provided earlier. Considering both sample lots, the most noticeable effect attributed to sample size was on MC and percentage of deformed kernels, which were greater for the 170-g batches than the 470-g counterparts. Parboiling with 320-g sample loads resulted in values that were intermediate of the 170-g and 470-g batches. The difference in MC and percentage of deformed kernels may be attributed to the rates of hydration and heat transfer that may likely be more efficient with a small sample size (170 g vs. 470 g). Islam et al. (2002) suggested that sample size affects the rates of hydration and heat transfer such that a shorter duration (3 min vs. 7 min) was required to attain a desired rough rice temperature of 99°C when a smaller sample size (200 g vs. 400 g) was used in their experiment.

The effect of sample size on HRY was not significant, although considerable improvements in HRY due to parboiling (both PU and autoclaving tests) relative to the non-parboiled samples were observed (table 2). HRY increased by 14.5-16.3% percentage points for the Harrisburg lot, and 4.4-4.8% percentage points for the Weona lot. The percentage point increase was greater for Harrisburg lot since the HRY of its non-parboiled sample was significantly less. Actual HRY values of parboiled samples were in fact greater for the Weona lot, regardless of sample size.

Across sample size, MC, percentage of deformed kernels, and L* and b* values were greater for Harrisburg in comparison to the Weona lot (table 2). These trends are consistent with the data on percent chalk of the non-parboiled samples, which was also greater for the Harrisburg lot (8.9% vs. 4.3%). Considering that the two lots were of the same cultivar and obtained from the same crop year, it appears that some factors during crop production affected their suitability for parboiling. Overall, the Weona lot had better parboiling characteristics than the Harrisburg counterpart. It follows that a good-quality rice to start with, also produces a better parboiled product.

IMPROVEMENTS IN THE PU DESIGN

Traditionally, a laboratory-scale parboiling procedure begins with hydrating rice in a beaker of water, followed by heating in a water bath, draining the soaking water, pressure-steaming with an autoclave, and drying the rice by a suitable method (Biswas and Juliano, 1988; Patindol et al., 2008). An advantageous feature of the PU described herein is that soaking, draining, and steaming are all performed in the same container in a single tank, thus providing convenience, and minimizing losses and variability in product quality from one batch to another. The PU automates the primary parboiling cycle operations, maintaining continuous process conditions during soaking and steaming that are analogous to plant-scale processing operations used in the rice industry. This automation also decreases experimental variability due to different operators and parboiling replications.

There are some aspects of the current PU design that could be improved. Less critical enhancements may include a quick-opening door to replace the existing swing-bolt-hinged closure that requires a heavy-duty, expensive o-ring for sealing. Also, due to the fact that the water level sensors occasionally registered inaccurate water level data when condensation from steam triggered the sensors, the water level sensors may be replaced with a model that can withstand high temperature-pressure conditions of the parboiling cycle and still accurately indicate water level inside the tank. To prevent the sample-container parboiling performance variation shown in table 1, a baffle plate, or some sort of diverting mechanism, may be installed below the water and steam inlets at the top of the PU tank so that incoming hot water and steam will flow toward the sides of the tank and not directly into the upper sample containers. Alternatively, a diffuser with swirling flow may be installed at the inlets to provide more uniform steam distribution.

Table 2. Effect of sample size (mass of rough rice per container at the C3 position, as described in fig. 2) on the properties of parboiled rice using cultivar CL151 sample lots harvested at Harrisburg, Ark. (CL151-H) and Weona, Ark. (CL151-W)[a], [b].

Sample Lot	Sample Load Mass (g)	Moisture Content[c] (%)	Deformed Kernels (%)	Head Rice Yield (%)	L* (lightness)	b* (yellowness)
CL151-H	170	39.7 ± 0.9^a	28.5 ± 0.8^b	66.0 ± 1.3^b	55.3 ± 0.4^c	27.0 ± 0.5^a
	320	39.0 ± 1.0^{ab}	27.2 ± 1.5^b	66.3 ± 2.0^b	55.8 ± 1.0^c	26.6 ± 0.4^a
	470	38.0 ± 0.9^b	24.1 ± 1.8^c	67.8 ± 0.9^b	56.4 ± 1.0^c	26.3 ± 0.6^a
	Autoclaved[d]	35.5 ± 0.7^c	34.5 ± 2.1^a	67.3 ± 2.1^b	54.4 ±0.9^d	27.3 ± 0.3^a
	Non-parboiled	-	-	51.5 ± 1.1^c	76.1 ± 0.8^a	14.7 ± 0.3^c
CL151-W	170	37.7 ± 0.9^b	17.3 ± 0.7^d	70.6 ± 1.0^a	54.4 ± 1.4^d	25.0 ± 0.6^{ab}
	320	36.6 ± 0.7^{bc}	16.8 ± 1.2^{de}	70.8 ± 0.7^a	54.1 ± 0.8^d	24.0 ± 0.5^b
	470	36.0 ± 0.8^c	15.0 ± 1.1^e	70.5 ± 0.6^a	54.7 ± 1.2^d	24.0 ± 0.6^b
	Autoclaved[d]	33.2 ± 1.0^d	25.9 ± 1.1^c	70.9 ± 1.5^a	52.9 ± 1.2^e	26.2 ± 0.4^a
	Non-parboiled	-	-	66.1 ± 0.6^b	73.5 ± 0.3^b	15.7 ± 0.3^c

[a] Values are means from duplicate measurements of two replicate tests ± standard deviations.
[b] Means in a column followed by a common superscript letter(s) are not significantly different at P <0.05 based on Tukey's HSD test.
[c] Rough rice moisture content (wet basis) immediately after parboiling.
[d] Sample parboiled by autoclave steaming.

SUMMARY AND CONCLUSIONS

The quality attributes of parboiled rice processed by the PU were either similar or better than those of the product prepared by laboratory autoclave steaming. Performance test results indicated that the steam inlet design of the unit may be responsible for the observed variations in product properties due to sample container location. Overall, the newly-developed PU has some pertinent features that make it a valuable tool for rice processing research. The unit is designed such that temperature and pressure measurements are accurately controlled and recorded for the entire duration of each parboiling cycle, ensuring minimal variability among replications and providing explanatory process data when deviations in processing conditions occur. A custom-designed user interface allows practitioners to readily select soaking and steaming conditions, as well as to observe the progression of the parboiling operations. The programmatic intention was to create a system that could be reproduced and used at various sites, including both research laboratories and commercial production facilities. Having several PUs would improve experiments by allowing results to be verified at multiple locations. Having a PU on site would also allow research to determine processing setpoints and conditions before industrial-scale runs are made, thereby, possibly improving commercial parboiled rice quality. The PU could also be used to explore the potential processing characteristics of new rice cultivars on a small scale and therefore, allow experimentation that would be timely, more useful to breeders, less expensive, and not limited by plant logistics.

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