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Drying Characteristics and Milling Quality of Rough Rice Dried in a Single Pass Incorporating Glass Transition Principles

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The objective was to study the drying characteristics and milling quality of rough rice subjected to single-pass drying while controlling kernel material states. Drying experiments were conducted at 60, 70, and 80°C and relative humidities ranging from 13 to 83%. For all drying air temperatures and tempering conditions, milling quality was not significantly different from the controls when the relative humidity of the drying air was maintained above 63% (kernel core and surface maintained in a rubbery state) and rice was tempered immediately after drying, in sealed plastic bags and at the drying air temperature, for at least 60 min.

Keywords Drying; Glass transition; Relative humidity; Single pass; Tempering

INTRODUCTION

Drying rough rice to safe storage levels is one of the most important postharvest operations because it influences the subsequent handling processes, milling quality, and commercial value of the rice crop.[1] A minimal reduction in milling quality is often observed when rough rice is dried using unheated air.[2,3] At low drying air temperatures, kernel fissuring and breakage during subsequent milling is minimized. However, because of the long durations and limited dryer capacities, the use of low drying air temperatures may not be practical for commercial facilities. To maximize dryer throughput, which is desirable from a logistical standpoint,[4,5] higher drying air temperatures are used in commercial cross-flow systems to dry rough rice.[6,7] Heated air facilitates shorter drying durations but has the potential of reducing milling quality if not properly implemented.[6,7] Schluterman and Siebenmorgen[7] described a commercial cross-flow dryer operating at drying air temperatures ranging from 40 to 65°C in multiple passes that lasted approximately 20–40 min each. They found that samples located next to the hot air plenum were more likely to be over dried and of lower milling quality compared to samples located further from the hot air plenum due to exposure to high temperatures that caused changes in the material state of the kernels.

Studies have shown that the amount of moisture that can be removed in each drying pass without adversely impacting milling quality is largely dependent on the moisture content (MC) of the kernels.[6,8–11] Kunze[6] showed that rough rice at 20% initial MC can be dried to safe storage levels with minimal reduction in milling quality as long as the MC is reduced by a maximum of 1.5% per hour; greater moisture removal rates resulted in significant reductions in milling quality. Cnossen et al.[12] and Schulterman and Siebenmorgen[10] observed a similar reduction in milling quality when large amounts of moisture were removed from rice within a short duration. The authors hypothesized that a rapid reduction in MC led to the development of large moisture gradients from the surface to the core of the rice kernel. These moisture gradients in turn produced different material states between the kernel surface and the core, thereby generating stresses within the kernel that resulted in fissuring and subsequent breakage during milling. The material state transformation described by the authors is commonly referred to as the *glass transition*.

Glass transition, an important principle in polymer applications, is key to understanding high-temperature drying characteristics of starchy grains.[10,13,14] At low temperatures or MCs, starch granules behave as a glassy material due to limited molecular motion of the amylose and amylopectin polymer chains. The addition of thermal energy initiates molecular motion within the starch granules, which, when excessive, causes the polymer to become viscous, rubbery, and flexible.[13] This change in polymer conformation from a glassy to a rubbery material is referred to as glass transition and is accompanied by a large increase in the thermal conductivity,[15] expansion coefficient,[16] and moisture diffusivity; hence the fast drying rates observed when drying rice at elevated

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temperatures.[12,17] Glass transition is reversible and thus heated polymers can transition from a rubbery to a glassy state when cooled below transition temperatures[15] or when the MC decreases beyond a certain level.[13] Perdon et al.[16] and Siebenmorgen et al.[4] developed state diagrams that showed increasing glass transition temperatures with decreasing MC of brown rice.

Yang and Jia[18] and Jia et al.[19,20] mapped glass transition within a rice kernel during drying and showed that in the rubbery state, the kernel periphery dried much faster and reached equilibrium with the drying air within a shorter duration compared to drying in the glassy state. The rapid loss in moisture was accompanied by transition of the surface layers from a rubbery to a glassy material, whereas the core remained as a rubbery material. With extended drying, greater proportions of the kernel periphery transitioned from a rubbery to a glassy material, creating tensile and compressive stresses on the surface and core, respectively. The tensile stress along the longitudinal axis peaked and persisted throughout drying, eventually initiating fissuring on the kernel surface.[18–20] Schluterman and Siebenmorgen[10] and Cnossen et al.[14] observed similar material failure and fissure initiation through laboratory experiments designed to produce situations in which large proportions of kernel surface layers transitioned from a rubbery to a glassy material during high-temperature drying.

Considering the great intra-kernel material state differences and the resultant stresses that can be created during high-temperature drying, it is reasoned that by controlling kernel material states during the drying process, the stresses generated within a rice kernel can be minimized. Maintaining the entire kernel as a rubbery material throughout high-temperature drying would prevent intra-kernel stress development due to differences in material states between the surface and the core of the rice kernel, which has the potential of minimizing fissuring and facilitating maximum moisture reduction within the shortest time. If realized, this drying approach would conceivably make it possible to dry rough rice from harvest MC to safe storage levels in one pass with minimal reduction in milling quality. Keeping the rice kernel in a rubbery state during drying without allowing surface layers to transition to a glassy state can be implemented by control of the drying air relative humidity (RH). The temperature and RH of the drying air determine the equilibrium moisture content (EMC) of rice exposed to that air; that is, the greater the RH, the greater the rice EMC at a given temperature. Based on the state diagram developed for rice by Siebenmorgen et al.,[4] high RHs (>63%) will maintain the EMCs associated with high-temperature (60°C) drying air in the rubbery state, whereas low RHs will maintain EMCs in the glassy state at this temperature (Fig. 1). Shortly after the onset of drying, the MC of the outermost layers of a

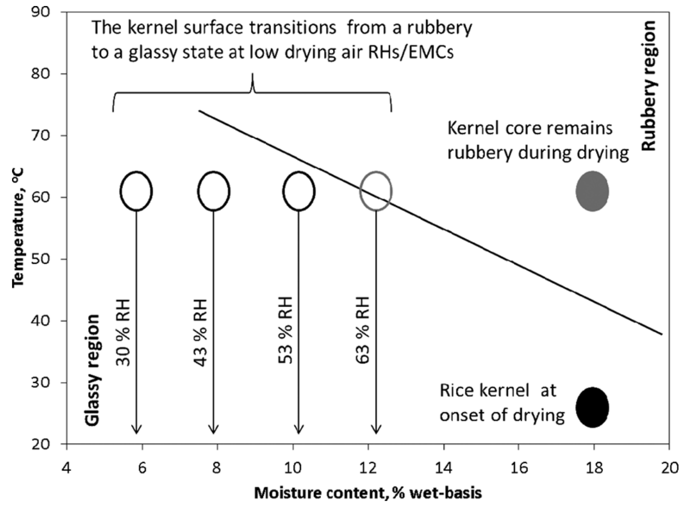

FIG. 1. Hypothetical material state differences between the surface and the core of a rice kernel caused by the relative humidity (RH)/equilibrium moisture content (EMC) associated with the drying air. The glass transition diagram was taken from Siebenmorgen et al.[4]

rice kernel will reach equilibrium with the drying air. If the EMC of the drying air is above the glass transition, the outermost layers will remain in a rubbery state throughout the drying process, as does the core, thereby minimizing the intra-kernel stresses created by material state differences.

Tempering immediately after drying, a common practice in large drying facilities, can be applied to further minimize the internal stresses within a kernel.[9,10,17,21] Tempering allows moisture concentrated in the kernel core to diffuse to the outer layers, resulting in less difference in MC and material states between the surface and core. Tempering durations depend on the rate of moisture migration from the core to the surface of rice kernels, which depends on kernel tempering temperatures and MCs; that is, greater temperatures and MCs result in shorter tempering durations.[11,12,17,19,21,22] Generally, a more uniform intra-kernel moisture distribution results in reduced fissuring and is achieved when the tempering duration is prolonged at any temperature.[12] Imprasit and Noomhorm[21] showed that the milling quality of rice dried at elevated temperatures (>60°C) and then tempered for prolonged durations (>2 h) was not significantly different from the milling quality of shade-dried samples (26–35°C).

By incorporating glass transition principles during drying, followed by immediate tempering, the main objective of this study was to develop a method that could be used to dry rough rice in a single pass with minimal reduction to milling quality. This approach could make the commercial drying process more efficient by reducing the number of passes and tempering steps.

LAYOUT OF THE STUDY

The overall design of the study is shown in Fig. 2. A series of preliminary experiments was conducted to establish appropriate equipment and procedures for the primary experiment. The first such experiment was conducted to establish drying curves for the three rice lots used in the study. Rice samples were dried from initial MC until EMC was reached for a given drying air condition. From the drying curves, the drying durations required to attain 12.5% MC were estimated for each lot and drying air condition.

The second preliminary experiment was conducted to establish a suitable tempering procedure. Ideally, the tempering duration must be long enough to allow even distribution of moisture across the kernel, which would render the surface and core to be of similar material states, thereby reducing the intra-kernel stresses created by material state differences. The tempering conditions were thus designed to produce situations whereby the intra-kernel stresses were either adequately or inadequately reduced to prevent fissuring. In addition, tempering temperatures and RHs are critical in high-temperature drying processes due to the likelihood of the kernel surface transitioning from a rubbery to a glassy state if the EMC associated with the air within the tempering container is not maintained above the glass transition. Maintaining a high EMC within the tempering container minimizes continued moisture diffusion from the kernel surface during tempering. The tempering temperatures should be the same as the drying air temperatures or maintained above the glass transition to prevent the surface layers from transitioning from a rubbery to a glassy state. Tempering at temperatures above the glass transition also facilitates faster moisture equilibration across the kernel due to greater moisture diffusivity levels in the rubbery vs. glassy state.

To investigate the effect of glass transition of surface layers during tempering, the milling quality of samples tempered under three different conditions was compared. Fissuring and a subsequent reduction in milling quality were expected to be greater in kernels whose surface layers transitioned from a rubbery to a glassy state during tempering compared to kernels that remained in a rubbery state throughout tempering. The first tempering condition studied incorporated a large headspace that allowed moisture migration from the kernel surface into the air within the container throughout tempering; this would cause a large proportion of the surface layers to lose moisture and thus transition from a rubbery to a glassy state. The second condition incorporated a much smaller headspace compared to the first condition, thus limiting moisture loss

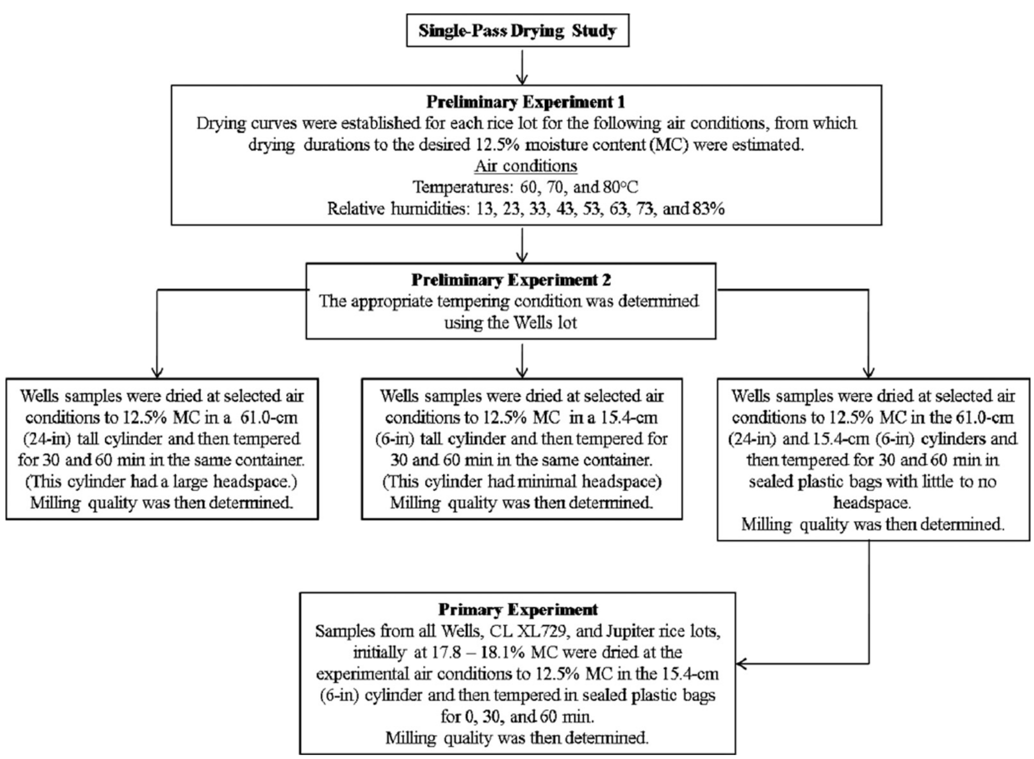

FIG. 2. Experimental design of the single-pass drying study. The drying characteristics and milling quality of pure-line long-grain Wells and hybrid CL XL729, and pure-line medium-grain Jupiter initially at 17.8–18.1% moisture content was investigated.

from the kernel surface, only causing relatively smaller proportions of the kernel surface layers to dry and transition from a rubbery to a glassy state. Therefore, samples tempered in the limited-headspace container were expected to be of better milling quality compared to samples tempered in the large-headspace container. The third condition incorporated a sealed and impermeable container with little to no headspace in which the resulting RH would be at a high level throughout tempering, thereby preventing moisture loss from the kernel surface and keeping the entire kernel in a rubbery state throughout tempering. Samples tempered in the high-RH, airtight container were expected to be of better milling quality than samples tempered in the large- and limited-headspace containers because minimal intra-kernel stress would be generated by the much reduced material state differences between the kernel surface and core.

Rice, cv. Wells, samples dried in a single pass to 12.5% MC at selected drying air conditions (Fig. 2) were tempered under each of the three tempering conditions immediately after drying; that is, one tempering condition per sample. Subsequently, milling quality was compared among the three tempering conditions. The sealed/airtight container was selected for the primary experiments because samples tempered therein exhibited the least reduction in milling quality. A detailed description of the preliminary and primary experiments follows.

MATERIALS AND METHODS

Sample Collection and Preparation

Long- and medium-grain pure-line cultivars, Wells and Jupiter, respectively, and a hybrid long-grain cultivar, CL XL729, were harvested from Stuttgart, Arkansas, in the fall of 2010 at MCs ranging from 17.8 to18.1% (wb; moisture content is expressed on a wet basis unless specified otherwise.). All samples were cleaned (MC Kicker Grain Tester, Mid-Continent Industries, Inc., Newton, KS) and stored in sealed plastic tubs (0.22 m^3) at 4°C for 2 months. Prior to each drying trial, samples were withdrawn from storage, sealed in plastic bags, and allowed to equilibrate to ambient temperature (24°C) overnight. The MC of the rice samples was then measured by drying duplicate 15-g subsamples for 24 h in a convection oven (1370 FM, Sheldon Mfg., Inc., Cornelius, OR) maintained at 130°C.[23]

Drying Air Conditions

A wide range of RHs was selected to maintain the kernel surface as either a glassy or rubbery material during drying in order to observe the effects of material state differences between the core and the surface on milling quality. Considering that the outermost layers of the kernel surface reach an EMC associated with the drying air shortly after the onset of drying, high RHs (>63%), which would yield EMCs above the glass transition at constant temperature (Fig. 1), were expected to prevent the surface layers from transitioning from a rubbery to a glassy state, thereby minimizing intra-kernel stresses created by material state differences. Low RHs, which would yield EMCs below the glass transition at constant temperature, were hypothesized to cause rapid transitioning of the surface layers from a rubbery to a glassy state during drying (Fig. 1), thereby generating the previously described differential stresses within the kernel that, when sufficiently severe, cause fissuring. For this study, rough rice samples were dried at RHs of 13, 23, 33, 43, 53, 63, 73, and 83% and temperatures of 60, 70, and 80°C. High drying air temperatures were selected because of the resultant fast drying rates.

Drying System

A schematic of the system used to conduct the drying experiments is shown in Fig. 3. The apparatus consisted of a controller (ESL 4CA Platinous Temperature and Humidity Chamber, Espec, Hudson, MI) capable of automatically maintaining temperature in the range of −35 to 150°C (±0.5°C) and RH in the range of 6 to 98% (±1%) within a 900-L chamber. The air in the chamber was circulated at 0.38 $m^3s^{-1}$to minimize stratification within the chamber. Air conditions were monitored using a digital temperature and RH probe (Hygro-M2, General Eastern, Woburn, MA). The probe was calibrated using potassium sulfate, sodium chloride, and lithium chloride (Merck, Darmstadt, Germany) prior to the experiments.

A metal cylinder, 20.3 cm (8 in) in diameter and 61.0-cm (24-in.) tall, with a perforated floor, a movable lid, and wrapped with 2-mm (0.02-in.)-thick ceramic fiber insulation (Zirconia Felt ZY-50, Zircar Zirconia, Inc., Florida, NY), was used for establishing the rough rice drying curves. A metal screen, similar in construction to the perforated floor, was fastened to the top opening of the cylinder directly below the movable lid to prevent inadvertent removal of fluidized kernels. This drying apparatus was placed inside the environmental chamber and mounted onto a metal plenum. A 25.4-cm (10-in.)-diameter centrifugal fan (4C108, Dayton Electric Manufacturing Co., Niles, IL) coupled to a 0.56-kW (0.75-hp), three-phase electric motor (3N443BA, Dayton Electric Manufacturer Co.) was mounted outside the chamber to avoid exposure to high temperatures. This fan suctioned air at the set temperature and RH from the chamber through a port located in the chamber wall and then passed the exhaust air through a second port in the chamber wall connected to the plenum beneath the drying cylinder. The desired air flow rate through the drying cylinder was achieved by regulating the electrical frequency of the fan motor using a frequency inverter (AF-300 Mini, GE Fuji Drives USA,

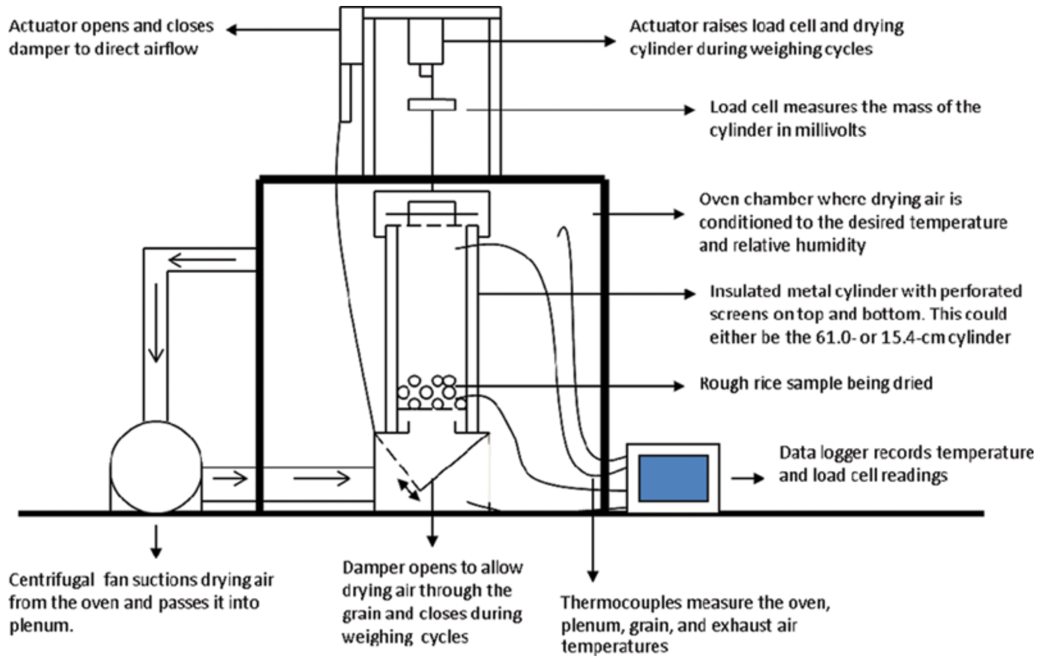

FIG. 3. Schematic of the fluidized bed drying system (color figure available online).

Salem, VA), which controlled the motor and fan shaft rotational speed.

A spring-loaded damper constructed in the metal plenum (Fig. 3) controlled the air flow direction by either diverting air through the drying cylinder's perforated floor or closing off the perforated floor, allowing the air to empty into the environmental chamber. Opening and closing of the spring-loaded damper was controlled by a linear actuator (damper actuator; LACT4P, SPAL USA, Ankeney, IA) mounted outside the environmental chamber and connected to the damper by a cable that passed through a port in the chamber ceiling. A second linear actuator (load cell actuator) mounted outside the environmental chamber and directly above the drying cylinder was coupled to a 178-N (40-lb_f) full-bridge, thin-beam load cell (LCL-040, Omega Engineering, Inc., Stanford, CN) that was attached to the drying cylinder via a cable that passed through a second port in the chamber ceiling.

At specified durations, the damper actuator was activated to raise the damper, thereby preventing air flow through the rice sample. The load cell actuator was then activated to suspend the drying cylinder just above the drying apparatus plenum. After a stabilization period, the mass of the drying cylinder and sample were recorded as a millivolt signal from the load cell. Voltage data were converted to masses using a previously established calibration. Temperature and load cell data were collected using a data logger (21X micro logger, Campbell Scientific, Salt Lake City, UT).

Measurement of Air Flow Rates

Prior to the drying trials, fan performance tests were conducted using a metal duct, 15.2 cm (6 in) in diameter and 1.8 m (6 ft) in length, to establish the relationship of the fan motor electrical frequency to the air flow rate of the circulation fan. Air flow rates of 80, 220, and 785 cfm/ft^2 were obtained by setting the fan motor electrical frequency at 10, 20, and 44 Hz, respectively. The average air velocity in the test duct was measured using a hot-wire anemometer (8450-13E-V-STD-NC, Control Co., Friendswood, TX).

The following procedure[24] was used to determine minimum fluidization velocity at 60, 70, and 80°C air temperatures:1.11 kg of rough rice, required to attain a 5.1-cm (2-in.) grain depth, was poured into a transparent cylinder, similar in construction to the previously described 61.0-cm (24-in.)-tall metal cylinder, which allowed for visual observation of rough rice fluidization. The fan was activated and the air velocity was increased to vigorously fluidize the bed of rice. The air velocity was then slowly decreased until the fluidized bed was reduced to a fixed bed. The pressure drop at different depths across the 5.1-cm (2-in.)-rice bed was determined by inserting a static pressure probe (PX270, Omega Engineering Inc., Stamford, CT) from the top of the cylinder as the velocity was being decreased. At minimum fluidization velocity, the pressure drop at different bed depths was constant and the weight of rice was supported by the air flow.[21] An air flow rate of 785 cfm/ft^2($3.99\ m^3 s^{-1}/m^2$) was found to fluidize a 5.1-cm (2-in.)-rough rice bed. This air flow rate was consistent for all rice cultivars and drying conditions and was thus used throughout the study.

Preliminary Experiment 1: Drying Curves and Durations to Attain 12.5% MC

A 1.11-kg (2.45-lb_m) rice sample was placed in the 61-cm (24-in.)-tall metal cylinder. The drying cylinder was then placed inside the environmental chamber and attached to the load cell actuator. The chamber control system was activated to establish the desired temperature and RH air conditions within the chamber. During this stabilization period, the damper actuator was activated to set the spring-loaded damper in the closed position, thus blocking air from passing through the rice sample. Once the chamber temperature and RH were stabilized, the combined mass of the drying cylinder and initial mass of the rice sample was measured by activating the load cell actuator. At the end of the weighing cycle, the damper actuator was deactivated, which allowed air flow through the drying cylinder to initiate drying (Fig. 3).The weighing procedure was repeated every 5 min for the duration of a drying trial until the change in mass was negligible (less than 0.01 g). The mass data were then converted to MCs based on the initial rough rice sample mass and MC at the start of the drying trial. Drying curves (MC vs. drying duration) were plotted for each rice lot at all air conditions specified in Fig. 2 and the durations required to attain 12.5% MC were determined. Each drying run was replicated.

Preliminary Experiment 2: Establishing Appropriate Tempering Conditions

Only the Wells lot was used for these tests. Three tempering conditions were investigated (Fig. 2). Samples were tempered for 0, 30, and 60 min, after which they were spread in thin layers and allowed to cool at 24°C and 38% RH. In the first tempering condition, rough rice samples were dried and tempered in the 61.0-cm (24-in.)-tall metal cylinder, which had a large (22-in.) headspace that allowed for moisture migration from the kernel surface layers into the air within the cylinder during tempering. In the second condition, samples were dried and tempered in a 15.4-cm (6-in.)-tall metal cylinder, similar in construction to the 61.0-cm (24-in.)-tall cylinder but with a movable lid that fell onto the rough rice samples when the drying air flow was diverted by raising the damper, thus reducing headspace and minimizing moisture migration from the kernel surface during tempering. The second condition was, however, not airtight due to the marginal clearance between the edge of the lid and the inner circumference of the cylinder that allowed the lid to slide upwards during drying and downwards during tempering. Limited moisture escape from the drying container during tempering was likely to occur via this clearance. In the third condition, samples dried in both cylinders were manually transferred into3,785-cm^3 (1-gal.) Ziploc plastic bags immediately after drying; air was manually expressed, after which the bags were sealed and returned to the drying chamber, where tempering was conducted at the drying air temperature. The transfer of rice from the drying containers into plastic bags immediately after drying was rapid, thus minimizing loss of moisture and energy. At the end of each tempering trial, samples were spread in thin layers and exposed to ambient air at approximately 24°C and 38% RH for 10 min. Each test was replicated.

All samples were stored for a week in cold storage (4°C) before milling quality analysis. Post drying fissuring studies have shown that kernel fissures were mostly visible 24 to 48 h after drying, thereby justifying the practice of delaying milling quality analysis for more than 48 h after drying.[25–27]

Additional tests were conducted to determine whether inadvertent cooling during the actual transfer of rice from the drying containers into plastic bags affected milling quality. Samples from the Wells lot were dried in a single pass to 12.5% MC using air at 70°C and 13, 23, 33, and 43% RH using the 15.4-cm (6-in.) cylinder. At the end of drying, the transfer of rice samples into plastic bags was delayed for 0, 60, 120, and 180 s; during these periods, samples were spread in thin layers and exposed to ambient air (24°C and 38% RH).The samples were then transferred into plastic bags and tempered for 60 min at the drying air temperature. After tempering, samples were again spread in thin layers and exposed to ambient air for 10 min. The samples were then stored for a week in cold storage (4°C) before milling quality analysis. Each test was replicated.

Primary Experiment: Effect of Single-Pass Drying on Milling Quality

The 15.4-cm (6-in.) metal cylinder was used in the primary experiment (Fig. 2). Rough rice samples from all three lots were dried in a single pass to 12.5% MC using air at 60, 70, and 80°C and 13, 23, 33, 43, 53, 63, 73, and 83% RH. Immediately after drying, samples were transferred from the drying container into plastic bags and tempered at the drying air temperature for 0, 30, and 60 min. Additional samples from the Wells lot were dried at 70°C and 13, 23, 33, 43, 53, and 63% RH and tempered in plastic bags for 120 min to determine whether extended tempering further improved milling quality. After tempering, samples were spread in thin layers and exposed to ambient air at 24°C and 38% RH for 10 min. The samples were then stored at 4°C before milling as described previously. Each drying and tempering condition was replicated. Control samples from each lot were spread in thin layers on screens and gently dried at 26°C and 54% RH from initial MC to 12.5% MC.

Milling Analysis

Duplicate 150-g subsamples of rough rice, obtained from each sample dried to 12.5% MC, were dehulled using a laboratory huller (Satake Rice Machine, Satake Engineering Co., Ltd., Tokyo, Japan), milled for 30 s using a laboratory mill (McGill #2, Rapsco, Brookshire, TX), and aspirated for 30 s using a seed blower (South Dakota Seed Blower, Seedboro, Chicago, IL). Head rice was then separated from broken kernels using a double-tray sizing machine (Grainman, Grain Machinery MFG, Miami, FL). Head rice was considered as kernels that remained at least three fourths of the original kernel length after milling.[28] Head rice yield (HRY) was calculated as the mass proportion of rough rice that remained as head rice after complete milling.

Statistical Analysis

The experimental variables included rice cultivar (pure line and hybrid), cultivar type (medium grain and long grain), air conditions (temperature and RH), and tempering conditions and times. The effects of all variables on milling quality were determined using analysis of variance (ANOVA; JMP 8.0.1. SAS Institute, Cary, NC). Significant differences between sample means were established using Tukey's test at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Preliminary Experiment 1: Drying Curves and Durations to Attain 12.5% MC

The durations required to dry the three cultivars, initially at 17.8–18.1% MC, to 12.5% MC using air at 60, 70, and 80°C and 13–83% RH, are shown in Fig. 4. In general, shorter drying durations were observed with increasing temperatures and decreasing RHs because of the resultant low rough rice EMC, which formed the driving force for both liquid and vapor transfer from the porous rice kernels.[29] Drying durations increased exponentially with increasing RH at constant drying air temperatures because of the increasing rough rice EMCs.

Overall, the time required for single-pass drying to 12.5% MC was less than that anecdotally observed for multipass drying methods. The average residence time of rice in a typical commercial cross-flow dryer is approximately 20–40 min per pass.[7] Multiple passes are required to reduce the MC to safe storage levels because only a small amount of moisture (<3%) can be removed in each pass to minimize fissure formation and maintain milling quality.[12] The rice is then tempered for extended durations between passes to minimize moisture gradients; generally, more than 24 h is required to dry high-MC rough rice to 12.5% MC. It is therefore evident that single-pass drying, even at high relative humidities, is faster than current multipass drying.

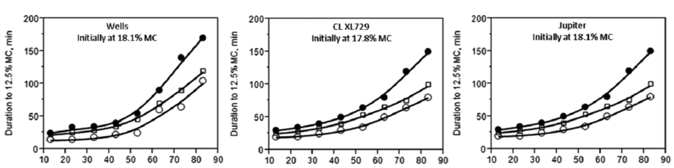

FIG. 4. Drying times required to attain 12.5% moisture content (MC) for Wells, CL XL729, and Jupiter rice samples, initially at 17.8–18.1% MC, dried at (●) 60°C, (□) 70°C, and (○) 80°C and 13–83% relative humidity. The drying durations were estimated from drying curves.

Preliminary Experiment 2: Establishing an Appropriate Tempering Condition

The HRYs of Wells samples dried at 70°C and 13% RH in the 61.0-cm (24-in.) and 15.4-cm (6-in.) cylinders, tempered in the cylinders and in sealed plastic bags for 0, 30, and 60 min immediately after drying, and exposed to ambient air for 10 min at the end of tempering, are shown in Fig. 5. As expected, longer tempering times resulted in greater HRYs for all tempering environments. In addition, better milling quality (p-value <0.05) was observed for samples tempered in sealed plastic bags than for samples tempered in either cylinder. For example, the HRYs of samples dried and tempered in the 15.4-cm (6-in.) cylinder for 0, 30, and 60 min were 25.5, 29.1, and 35.5%, respectively, whereas the HRYs of samples dried in the same cylinder but tempered in sealed plastic bags for the same durations were 23.9, 39.5, and 43.9%, respectively. Similar trends were observed for the 61.0-cm (24-in.) cylinder.

Tempering rice in sealed plastic bags was more effective than tempering in either cylinder because at the onset of tempering within the plastic bags, moisture loss from the rice kernels quickly saturated the limited air within the bags; this minimized the vapor pressure difference between the kernel surface and the interparticle air and prevented further moisture loss from the kernel surface. The high RH within the

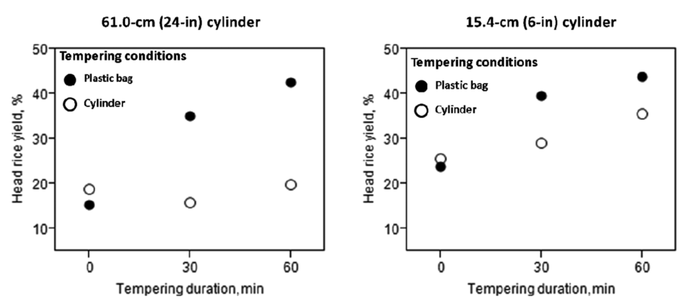

FIG. 5. Head rice yields of Wells samples dried at 70°C and 13% relative humidity to 12.5% moisture content in a single pass in either the 61.0-cm (24-in.) or 15.4-cm (6-in.) cylinder and then tempered in the 61.0-cm (large headspace) or 15.4-cm (small headspace) cylinder or a sealed plastic bag (minimal headspace). Data points are an average of four measurements; that is, two replications with each replicate head rice yield measured in duplicate. The head rice yield of the control was 51.2%.

tempering environment, coupled with the high tempering temperature (70°C), helped maintain both the surface and core in a rubbery state throughout tempering, thereby reducing intra-kernel stresses generated during drying. Similar results were reported by Cnossen et al.,[14] who observed that tempering at temperatures above the glass transition minimized loss in milling quality for rice dried at high drying air temperatures and fast moisture removal rates.

Likewise, samples tempered in the 61.0-cm (24-in.) cylinder had the lowest milling quality due to the large (22-in.) headspace, which allowed continuous moisture loss from the kernel surface during tempering. The loss of moisture caused a greater proportion of the surface layers to transition from a rubber to a glassy state, increasing the intra-kernel tensile and compressive stress differential generated during drying and thereby producing fissures.[9,18,19] Zhang et al.[30] observed that tempering rice kernels in the glassy state, even when using high temperatures, did not effectively relieve the tensile and compressive stress differential within the kernel and thus only improved milling quality to a limited extent.

Effect of Transfer Duration from the Drying Container into Plastic Bags

The HRYs of samples from the Wells lot, dried at 70°C and 13, 23, 33, and 43% RH to 12.5% MC in a single pass and exposed to ambient air for 0, 60, 120, and 180 s before being placed into plastic bags for tempering, are shown in Table 1. Loss of milling quality was only significant (p-value <0.05) for the 180-s exposure. Therefore, milling quality reductions due to the post drying/tempering container transfer process were significant only for durations greater than 120 s. The transfer duration for the primary experiment was less than 60 s; hence, milling quality reductions due to the post drying/tempering transfer process were considered negligible.

TABLE 1
Head rice yields of Wells rice samples dried at 70°C and the indicated relative humidities to 12.5% moisture content in a single pass

	Head rice yield (%)			
Relative humidity (%)	0 s	60 s	120 s	180 s
13	45.9[a]	44.3[ab]	44.6[ab]	43.4[b]
23	45.8[a]	44.6[ab]	44.1[ab]	43.4[b]
33	46.2[a]	45.0[a]	45.3[a]	45.2[a]
43	45.9[a]	45.9[a]	45.7[a]	43.9[b]

Immediately after drying, the samples were exposed to ambient air for 0, 60, 120, and 180 s before tempering in sealed plastic bags for 60 min, after which they were spread in thin layers and exposed to ambient air for 10 min. Head rice yields are an average of four measurements; that is, two replications with each replicate head rice yield measured in duplicate. Head rice yields are statistically compared within rows. Significant differences between sample means were established using Tukey's test at $\alpha = 0.05$. Values designated by the same superscript letter are not significantly different.

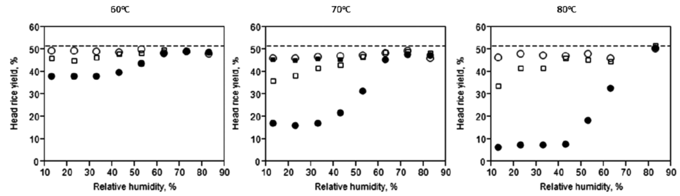

FIG. 6. Head rice yields of Wells rice samples dried at 60, 70, and 80°C and 13–83% relative humidity to 12.5% moisture content in a single pass. The samples were dried in the 15.4-cm (6-in.) cylinder and immediately tempered in plastic bags for (●) 0 min, (□) 30 min, and (○) 60 min. Additional samples dried at 70°C and 13–43% RH were tempered for 120 min (■). The control samples (—) were gently dried at 26°C and 54% relative humidity to 12.5% moisture content. Data points are an average of four measurements; that is, two replications with each replicate head rice yield measured in duplicate.

However, in a typical commercial cross-flow drying system,[7] rice exiting a dryer is normally exposed to ambient air as it is conveyed by unloading augers and bucket elevators to tempering/storage bins. The conveying process during which kernels are exposed to ambient air is most likely longer than 120 s and could be a cause for some milling quality reduction.

Primary Experiment: Effect of Single-Pass Drying on Milling Quality

The milling quality of the three rough rice lots, which were dried in a single pass at 60, 70, and 80°C and 13, 23, 33, 43, 53, 63, 73, and 83% RH to 12.5% MC followed by immediate tempering in sealed plastic bags for 0, 30, and 60 min, after which samples were spread in thin layers and exposed to ambient air for 10 min, is shown in Figs. 6 and 7. The milling quality improved with increasing RHs for all

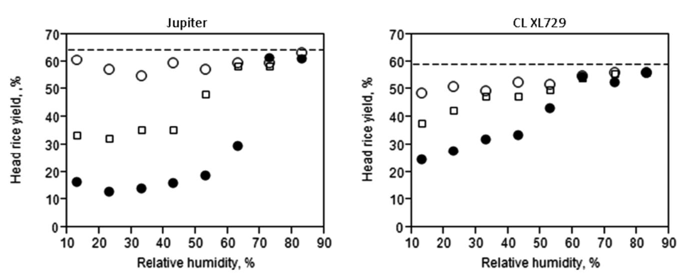

FIG. 7. Head rice yields of Jupiter and CL XL729 rice samples dried at 60°C and 13–83% relative humidity to 12.5% moisture content in a single pass. The samples were dried in the 15.4-cm (6-in.) cylinder and immediately tempered in plastic bags for (●) 0 min, (□) 30 min, and (○) 60 min. The control samples (—) were gently dried at 26°C and 54% relative humidity to 12.5% moisture content. Data points are an average of four measurements; that is, two replications with each replicate head rice yield measured in duplicate.

TABLE 2
Equilibrium moisture contents of rough rice estimated using the modified Chung–Pfost equation for temperatures of 60, 70, and 80°C and relative humidities of 13–83%

	Equilibrium moisture content (% wb)							
Temperature (°C)	13%	23%	33%	43%	53%	63%	73%	83%
60	6.5	7.4	8.1	8.8	9.6	10.4	11.3	12.6
70	5.5	6.4	7.2	7.9	8.6	9.4	10.4	11.7
80	4.8	5.7	6.4	7.2	7.9	8.8	9.7	11.1

The empirical constants *A, B*, and *C* of the modified Chung–Pfost equation were estimated by Ondier and Siebenmorgen.[33]

drying air temperatures. The trend was more prominent for samples tempered for 0 and 30 min compared to samples tempered for 60 min. The lower HRYs observed at 13–53% RH compared to 53–83% RH may be explained by intra-kernel stresses resulting from material state differences between the surface and core. Shortly after coming into contact with the drying air, the kernel reached drying air temperatures and transitioned from a glassy to a rubbery state. As indicated by Yang and Jia,[18] the MC of the outermost layers reduced rapidly to the low EMC associated with the drying air conditions (Fig. 1 and Table 2), whereas the core remained at a relatively high MC. A moisture gradient developed from the core to the surface of the kernel, which increased in magnitude as drying progressed due to increasing proportions of the surface layers reaching the EMC associated with the drying air.[18] The low surface MC caused the surface layers to transition from a rubbery to a glassy state while the core remained rubbery, creating material state differences within the kernel. The intra-kernel stresses resulting from the material state differences between the surface and the core caused increased kernel fissuring when rice was not tempered immediately after drying; hence the low milling quality observed after 0 min of tempering. Tempering for at least 30 min resulted in significant improvement in milling quality, which indicates that the 30-min tempering duration, though inadequate, helped reduce the intra-kernel stress differential. Tempering for at least 60 min resulted in much better milling quality compared to tempering for 0 and 30 min, which showed that the intra-kernel stresses were greatly reduced within this time. However, the milling quality of the samples dried at the low drying air RHs was still less than the control even after 120 min of tempering (Fig. 6), which indicates that the intra-kernel stress created by material state differences between the surface and the core during drying could not be completely eliminated during tempering.

The increasing HRYs observed when RH was increased from 53 to 83% were enabled by the greater rough rice EMC at the drying air conditions (Fig. 1 and Table 2), which maintained the kernel surface in the rubbery state. As such, the material state differences between the kernel core and surface were relatively reduced at high drying air RHs compared to drying at lower RHs; hence, less intra-kernel stress differential was created. At RHs greater than 63%, HRY was not significantly different from the control after 60 min of tempering. Similar results have been reported by Cnossen and Siebenmorgen,[9] who observed improved milling quality in samples dried using high RH/EMC air and tempered for at least 60 min.

Medium-Grain vs. Long-Grain Kernel Fissuring Susceptibility

The medium-grain cultivar, Jupiter, whose features include a shorter, thicker kernel, was more susceptible to fissuring after 0 and 30 min of tempering (Fig. 7) compared to the long-grain cultivars, Wells and CL XL729 (Figs. 6 and 7, respectively). For example, for drying air conditions of 60°C and 13, 23, and 33% RH and a tempering duration of 30 min, the HRYs of Wells samples were 46.2, 45.1, and 46.3%, respectively; the HRYs of CL XL729 samples were 37.8, 42.5, and 47.3%, respectively; and the HRYs of Jupiter samples were 33.5, 32.4, and 35.4%, respectively. Studies have shown that medium-grain kernels are more susceptible to fissuring than long-grain kernels.[8,27,31] Sun et al.[32] reported that medium-grain kernels showed greater nonuniform kernel length and thickness shrinkage during drying compared to long-grain kernels, which could be why medium-grain kernels are more susceptible to fissuring than long-grain kernels.

SUMMARY

The results of these experiments show that high drying air temperatures (>60°C) can be used to dry rough rice in a single pass with a minimal reduction in milling quality provided that samples are properly tempered for at least 1 h immediately after drying. Alternatively, maintaining a high drying air RH was shown to maintain the kernel surface and core in a rubbery state, thereby minimizing intra-kernel stresses caused by differences in material properties, thus preventing fissuring and fully maintaining milling quality. Proper tempering immediately after drying was shown to be critical because exposure of kernels dried at high temperatures to ambient air immediately after the cessation of drying for longer than 3 min resulted in significant milling quality reductions.

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