Application of X-ray Imaging and Glass Transition Principles in Understanding Rice Kernel Fissure Formation

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Application of X-ray Imaging and Glass Transition Principles in Understanding Rice Kernel Fissure Formation

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Food Science

by

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ABSTRACT

Rice kernels with internal fractures of the endosperm, fissures, tend to break during milling, leading to head rice yield (HRY) reductions. Minimizing kernel fissuring is thus an important goal of the rice industry. To minimize fissuring during the drying process, a better understanding of the fissuring process and the kinetics thereof is required. The goal of this research was to use X-ray imaging and glass transition principles to better understand rough rice kernel fissuring. First, because the instance when the fissuring process is initiated and completed during the drying process is not well known, an X-ray imaging setup that allows for in-situ rough rice drying was used to elucidate rough rice fissuring kinetics. For harsh drying air conditions, fissuring occurred and appear instantaneously whereas, for mild conditions, a time delay was required before fissures appeared. Second, a hypothesis known as the glass transition hypothesis has been used to explain fissure formation during the drying process. However, the hypothesis has not been validated from a fundamental fissuring standpoint. With the availability of an X-ray system for fissure visualization in rough rice kernels during the drying process, the glass transition hypothesis was evaluated. Results showed that the glass transition principles proposed to explain fissure formation are valid for various drying air temperatures, rice moisture contents (MCs), and drying air equilibrium MCs associated with rough rice. Third, tempering rice immediately after drying has been shown to minimize fissure formation. However, the effect of tempering on minimizing fissure formation has not been quantified. This study showed that drying followed by tempering can reduce kernel fissuring by up to 50% and increased the percentage points (pp) of MC reduction that can be safely achieved in a single drying pass by 1-2 pp. Finally, grain inverters have been used in commercial cross-flow dryers to improve MC uniformity across the grain column. However, the effect of grain inversion on fissuring and HRY reduction is not known and was therefore evaluated. Results showed that grain inverters in a
cross-flow dryer can significantly minimize fissuring and HRY reduction at plenum air temperatures between 55°C and 60°C.
ACKNOWLEDGMENTS

First and foremost, I would also like to take this opportunity to thank The Lord for His mercies and blessings; without Him, none of my accomplishments would have been possible. Likewise, I would like to extend my heartfelt and sincere gratitude to my advisor Dr. Terry J. Siebenmorgen for his relentless guidance, mentorship, and support throughout this research and for the numerous opportunities he provided me. My dissertation committee members Dr. Griffiths G. Atungulu, Dr. Andronikos Maromoustakos, Dr. Scott Osborn, and Dr. Ashok Saxena for their counsel that greatly contributed to the success of this research. Additionally, I would like to thank my family for supporting me and for always believing in me. Last but not least, my sincere gratitude goes to the rice quality lab staff and students for being such a great team to work alongside, and for their help in sample preparation and data collection.

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DEDICATION

To the memory of Dr. Terry J. Siebenmorgen for his kindness and love for humanity, and his devotion to agriculture and rice research.
TABLE OF CONTENTS

INTRODUCTION .................................................................................................................. 1
FIGURES AND TABLES ......................................................................................................... 5
REFERENCES .......................................................................................................................... 6
CHAPTER 1: Fissuring kinetics of rough rice during the drying process ................................. 8
ABSTRACT ................................................................................................................................. 8
INTRODUCTION ....................................................................................................................... 9
MATERIALS AND METHODS .................................................................................................. 11
  Sample preparation .................................................................................................................. 11
  Experimental setup ................................................................................................................ 12
  Experimental procedure ....................................................................................................... 12
RESULTS AND DISCUSSION ................................................................................................. 14
  Fissuring kinetics .................................................................................................................. 14
    Effects of tempering .......................................................................................................... 14
    Effects of drying air temperature and relative humidity ...................................................... 16
  Fissure characterization ....................................................................................................... 18
CONCLUSIONS ......................................................................................................................... 19
ACKNOWLEDGMENTS ............................................................................................................ 20
FIGURES AND TABLES ........................................................................................................... 21
REFERENCES ............................................................................................................................. 28
CHAPTER 2: Validating the glass transition hypothesis in explaining fissure formation in rough rice kernels during the drying process ................................................................................. 30
ABSTRACT ................................................................................................................................. 30
INTRODUCTION ....................................................................................................................... 31
MATERIALS AND METHODS .................................................................................................. 34
Sample preparation .................................................................................................................. 34
Experimental setup ................................................................................................................ 34
Experimental procedure .......................................................................................................... 35
Drying air equilibrium moisture content .................................................................................. 36
Rough rice initial moisture content .......................................................................................... 38
Drying air temperature .............................................................................................................. 39
CONCLUSIONS ....................................................................................................................... 41
ACKNOWLEDGMENTS .............................................................................................................. 42
FIGURES AND TABLES ............................................................................................................ 43
REFERENCES ............................................................................................................................ 51
CHAPTER 3: Effect of post-drying tempering of rice on minimizing kernel fissuring and maximizing moisture removal ............................................................................................................ 53
ABSTRACT .................................................................................................................................. 53
INTRODUCTION ........................................................................................................................... 54
MATERIALS AND METHODS ..................................................................................................... 56
Sample preparation .................................................................................................................... 56
Experimental procedure ........................................................................................................... 56
Statistical analyses ..................................................................................................................... 57
RESULTS AND DISCUSSION .................................................................................................... 57
Effect of tempering on maximizing moisture removal ............................................................... 59
Effect of tempering on minimizing kernel fissuring ................................................................. 61
CONCLUSIONS .......................................................................................................................... 64
ACKNOWLEDGEMENTS ............................................................................................................ 66
FIGURES AND TABLES .............................................................................................................. 67
REFERENCES ............................................................................................................................... 72
CHAPTER 4: Effect of grain inverters in cross-flow dryers on kernel fissuring and head rice yield reduction

ABSTRACT .................................................................................................................................. 74

INTRODUCTION .......................................................................................................................... 75

MATERIALS AND METHODS ....................................................................................................... 76
  Rice samples ................................................................................................................................. 76
  Laboratory dryer ......................................................................................................................... 77
  Drying runs ................................................................................................................................. 78
  Fissure detection and enumeration ........................................................................................... 81
  Milling analyses .......................................................................................................................... 82

RESULTS AND DISCUSSION ....................................................................................................... 83
  Fissured kernels .......................................................................................................................... 83
    Plenum air temperature ............................................................................................................ 83
    Number of grain inversions ...................................................................................................... 84
    Distance from the heated-air plenum .................................................................................... 84
  Head rice yield reduction .......................................................................................................... 86
    Tempering approach .............................................................................................................. 86
    Plenum air temperature ........................................................................................................... 87
    Number of grain inversions .................................................................................................... 87

CONCLUSIONS ............................................................................................................................ 88

ACKNOWLEDGEMENTS .............................................................................................................. 89

FIGURES AND TABLES ............................................................................................................... 90

REFERENCES ............................................................................................................................... 96

OVERALL CONCLUSIONS .......................................................................................................... 98
LIST OF PAPERS


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INTRODUCTION

Rice kernel fissuring is a major concern in the rice industry. Kernels with internal fractures of the endosperm, commonly referred to as fissures, tend to break during milling, leading to head rice yield (HRY) reductions. Fissured rice kernels are not only susceptible to breaking during milling, but also affect the functional properties of milled rice (Proctor and Goodman, 1985; Siebenmorgen et al., 2005; Mukhopadhyay and Siebenmorgen, 2017), causing post-milling processors to incur significant financial losses (Siebenmorgen et al., 2009). Kunze and Hall (1965) indicated that the commercial value of rice kernels with two or three fissures is significantly reduced. Additionally, Odek et al. (2017) reported that approximately 95% of the variation in HRY of rice samples is attributed to the presence of fissured kernels in samples. Therefore, minimizing kernel fissuring is an important goal of the rice industry.

Fissures caused by moisture desorption/improper drying of kernels has been proposed to be a result of material state differences between the inner core and the surface of the kernel, resulting in intra-kernel differential stress (Cnossen and Siebenmorgen, 2000). Cnossen et al. (2002) and Schluterman and Siebenmorgen (2007) proposed that rapid drying leads to large moisture content (MC) differences between the rice kernel surface and the core leading to different intra-kernel material states that cause stress.

Tempering has been shown to allow intra-kernel material state gradients to subside hence minimizing kernel fissuring. Cnossen et al. (2001) defined tempering as a holding process between drying passes that allow for MC gradients generated within the kernel during drying to subside. Tempering immediately after a drying pass allows moisture from the kernel core to diffuse to the outer layers, therefore minimizing internal kernel stress that could cause fissuring.
Material state diagrams, such as one shown in figure 1, can be used to predict the mechanical properties of kernels at given temperatures and MCs. As indicated by the material state diagram (Eq. 1) developed by Siebenmorgen et al. (2004), rice kernels exist as a glassy material at a temperature below the glass transition temperature \( T_g \), therefore exhibiting lesser expansion coefficients, specific volume, and diffusivity. As kernel temperature increases above \( T_g \), the kernel transforms from a ‘glassy’ to a ‘rubbery’ state and exhibits greater expansion coefficients, specific volume, and diffusivity (Slade and Levine, 1995; Zeleznak and Hoseney, 1987).

\[
T_g \text{ (brown rice)} = 101.2 - 3.33 \times \text{MC, } \%
\]  

(Eq. 1)

To fully incorporate glass transition principles in understanding rice kernel fissuring, validation of this hypothesis from a fundamental fissuring standpoint is required. However, prior to the availability of X-ray imaging equipment for fissure detection, the inability to visualize fissures in rough rice kernels during drying and tempering hindered validation efforts. Odek et al. (2018) used X-ray imaging to detect fissures in rough rice kernels during the drying process and showed that in-situ drying research might be useful for validating the glass transition hypothesis.

The maximum amount of moisture that can be removed from rice kernels in a single drying pass without a decrease in head rice yield (HRY) can be addressed using the glass transition hypothesis. Schluterman and Siebenmorgen (2007) proposed that the maximum allowable MC reduction depends on the drying air conditions, initial MC of the rough rice, and tempering durations. Jia et al. (2002) observed through finite-element modeling that there was a
quick reduction in MC at the kernel surface to the level of the equilibrium MC (EMC) of the
drying air, whereas MC at the center portion of the kernel was still relatively high even after a 60
minute exposure to drying air at 60°C and 17% RH. Jia et al. (2002) observed that during drying
at 60°C and 17% RH for 20 minutes, large MC gradients developed between the outer bran layer
and the kernel center leading to a HRY reduction of 5.6 percentage points (pp) when no
tempering was performed. However, on immediate tempering at 60°C for 40 minutes,
approximately 90% of the MC gradient was eliminated, leading to little to no HRY reduction.
The authors reported that a decrease in MC gradients led to a corresponding decrease in material
state gradients. Therefore, through proper tempering, there was a decrease in kernel fissuring and
consequently, a decrease in HRY reductions. The recommendations by Schluterman and
Siebenmorgen (2007) on the pp of MC reduction that can be achieved in one pass were based on
2 initial MCs and 2 drying air conditions. A study with a range of initial MCs, final MCs, drying
air conditions, and rice cultivars is needed to provide recommendations for various scenarios that
can typically be experienced in a commercial rice drying facility.

In cross-flow dryers, rice kernels at different locations across the column thickness dry at
different rates due to drastically different drying air conditions across the column. Rice kernels
closer to the heated-air plenum interact with hotter air and dry faster than kernels farther away
from the plenum; those kernels interact with cooler, more humid air. To improve uniformity in
drying, industrial-scale cross-flow dryers are often equipped with grain inverters (also called
turnflows or grain exchangers), which reverse the position of kernels in the column with respect
to the flow of drying air. While several authors have investigated the use of cross-flow grain
dryers, none of the studies investigated the role of grain inversions on kernel fissuring and HRY
reduction in relation to glass transition principles.
The goal of this research was to use an X-ray imaging system to study rough rice fissuring during drying and thus systematically validate the glass transition through a series of experiments. This dissertation is presented in a “published/submitted papers” format, wherein each chapter is a stand-alone paper that has been published or is in preparation for submission to a peer-reviewed journal. The objectives of this dissertation are as follows:

1) Chapter 1… Determine the kinetics of rough rice fissuring during the drying process and subsequent storage and characterize the configuration of fissures formed in rough rice kernels during drying and subsequent storage.

2) Chapter 2… Apply X-ray imaging to validate the glass transition hypothesis in explaining rough rice fissuring due to active drying using drying air conditions selected to allow different kernel portions to be at select regions of a rice material state.

3) Chapter 3… Determine the maximum percentage points (pp) of moisture content (PPMC) reduction that can be achieved in a single drying pass for tempered rice samples versus for non-tempered (immediately cooled) rice samples without causing severe kernel fissuring.

4) Chapter 4… Examine the role of grain inversion on rice kernel fissuring and head rice yield reduction in relation to the glass transition hypothesis.
FIGURES AND TABLES

Figure 1. The hypothetical path followed by a rice kernel during prolonged, high-temperature, low-relative humidity drying. Surface (S), midpoint (M), and center (C) correspond to locations within a rice kernel.
REFERENCES


CHAPTER 1

FISSURING KINETICS OF ROUGH RICE DURING THE DRYING PROCESS

Z. Odek, T. J. Siebenmorgen, A. Saxena

ABSTRACT

Fissuring of rough rice kernels leads to breakage during milling, which results in head rice yield reductions. While other studies have addressed the fissuring kinetics of milled rice kernels, rice is normally dried and stored as rough rice. Thus, the objective of this research was to study the fissuring kinetics of rough rice kernels during the drying process and to characterize the configuration of the fissures. Rough rice kernels of cultivar CL XL745 with a bulk moisture content of 17% were dried using air at 40°C, 50°C, and 60°C each at relative humidity (RH) levels of 20%, 40%, and 60%. During the drying process (drying, tempering, and subsequent storage), X-ray images of rice kernels were recorded to enumerate fissures. As the drying air temperature was increased, the percentage of fissured kernels increased for all RHs evaluated. Conversely, as RH was increased, the percentage of fissured kernels decreased. Approximately 90% of fissures appeared after drying had ceased, increasing rapidly in the initial 6 h after drying. Kernels dried at high-temperature, low-RH drying air combinations had fissuring occur and appear instantaneously during active drying. In low-temperature drying conditions, fissures did not appear during active drying. Fissuring under such conditions required a time delay after active drying. This study shows the stages of the drying process when fissures appear in rough rice and the durations after active drying when fissures are expected to appear.

Keywords: Glass transition, Post-drying, Relative humidity, Rice drying, Temperature, Tempering, X-ray imaging.
INTRODUCTION

Rice drying is an important post-harvest processing operation aimed at reducing the moisture content (MC) to levels suitable for safe storage and subsequent milling (Prakash and Siebenmorgen, 2019). Improper drying may result in quality losses such as fissuring (Henderson, 1954; Bautista et al., 2000) with consequent milling yield reduction (Aguerrer and Viollaz, 1986; Schluterman and Siebenmorgen, 2007; Odek et al., 2017). Minimizing fissuring during rough rice drying is thus an important goal of the rice industry.

Fissures in rice kernels are fractures of the kernel endosperm. There are generally two types of fissures that occur in rice kernels: transverse fissures (Sun et al., 2002; Kunze and Calderwood, 2004) and cross-wise fissures, also known as “turtle back” fissures (Stermer, 1968; Bautista et al., 2000). Transverse fissures are perpendicular to the long axis of a kernel, whereas cross-wise fissures appear in an irregular alignment. Henderson (1954) used X-ray imaging to study the causes and characteristics of rice fissuring and reported that fissures in rice kernels due to drying may be perpendicular to the major axis of the kernel, or in an irregular alignment. Cnossen et al. (2003), further characterized rice kernel fissures as either surface cracks or internal fissures. Surface cracks appear as tiny streaks on the kernel endosperm surface whereas internal fissures appear as longer cracks with either a transverse or an irregular, “turtle back” configuration.

Craufurd (1963), Ban (1971), and Kunze (1979) proposed that in drying of rough rice, a time interval after the completion of drying is required before fissures can be visually observed in the kernel endosperm. Subsequent studies have corroborated such observations. Sharma and Kunze (1982) reported that fissures visually formed in the kernel endosperm within 48 h after drying rough rice kernels at 60°C for 2 h. Similarly, Li et al. (1998) indicated that the percentage
of kernels that were visibly fissured increased rapidly during the initial 4 h after drying rough rice with no additional fissuring being observed after 48 h. Likewise, Siebenmorgen et al. (2005) reported that fissures visually appeared almost exclusively within the first 24 h after rough rice drying had been terminated and the fissuring process was completed within 48 h of termination of drying. The above-mentioned studies used an invasive method to be able to view fissures, which consisted of removing husks prior to observing fissures. Thus, different sets of rough rice kernels were evaluated at each time-point for a given drying and post-drying duration.

Various factors affect the number of fissured kernels and when the fissures appear in rice kernels during the drying process. For example, post-drying tempering has been shown to significantly reduce the number of fissured kernels (Schluterman and Siebenmorgen, 2007). Rice samples that are not tempered, but instead are allowed to cool immediately after drying, are expected to extensively fissure due to severe intra-kernel material state gradients that are created during prolonged drying and/or during cooling that immediately follows drying. It is difficult to differentiate between fissures caused by prolonged drying and those caused by post-drying cooling without tempering when the fissures are enumerated at the end of the drying process. Intra-kernel material state gradients are the differences in material properties within individual rice kernels due to temperature and MC gradients generated during drying (Slade and Levin, 1995; Perdon and Siebenmorgen, 1999). Rice kernel form i.e., rough, brown, or milled kernels, also affects the number of fissured kernels and when the fissures occur and appear during the drying process. Henderson (1972) and Lan and Kunze (1996) reported that rough rice kernels are less susceptible to fissuring than brown rice and milled rice kernels during both drying and re-wetting. These findings suggest that fissuring characteristics, trends, and kinetics for brown and milled rice would not accurately provide a conclusive understanding of the fissuring process in
rough rice, the form in which rice is typically dried. Thus, the objectives of this study were; 1) to determine the kinetics of rough rice fissuring during the drying process and subsequent storage, and 2) to characterize the configuration of fissures formed in rough rice kernels during drying and subsequent storage.

**MATERIALS AND METHODS**

**Sample preparation**

Long-grain rice cultivar CL XL745 was harvested at 19% MC† near Pocahontas, Arkansas in 2018 and cleaned using a dockage tester (XT4, Carter-Day Co., Minneapolis, Minn.) to remove material other than grain. The rice lot was then stored in a cooler at 4°C until experiments were conducted. Before the rice was used in drying experiments, it was conditioned to 17% MC using air at 30°C / 30% RH using a climate-controlled environmental chamber (ESL 4CA Platinous Temperature and Humidity Chamber, Espec, Hudsonville, Mich.). The drying durations required to attain a MC of 17% MC were approximated using a thin-layer drying equation developed by Prakash and Siebenmorgen, (2018). The drying air conditions were maintained by an environmental chamber. The chamber is capable of maintaining temperature in the range of -35°C to 150°C (±0.5°C) and RH in the range of 6% to 98% (±2.5%) at an airflow rate of 0.38 m³s⁻¹/m². The kernel-to-kernel MC distribution for each sample was then measured at least 24 h after conditioning was completed using a single-kernel moisture meter (CTR-500E, Shizuoka Seiki Co., Ltd., Tokyo, Japan) to verify that the majority of the kernels had attained 17%±0.5% MC.

† All moisture content values are expressed on a wet basis.
Experimental setup

The test system comprised the afore-mentioned environmental chamber that provided conditioned air for drying. The conditioned air was suctioned from the chamber using a fan (EcoPlus model 728459, Sunlight Supply, Inc., Vancouver, Wash.), then passed through an in-line heater (AHP-7561, Omega Engineering, Inc. Stamford, Conn.). The in-line heater was used to augment the environmental chamber in maintaining the desired drying air temperature and was controlled with a voltage regulator (3PN1010B, Staco Energy Products Co., Miamisburg, Ohio). The conditioned air was ducted into an X-ray system (UltraFocus 60, Faxitron Bioptics LLC., Tucson, Ariz.) within which a drying apparatus (Odek et al., 2018) was positioned. The drying apparatus was equipped with a data logger (Hobo Pro V2 U23-002, Onset Computer Corporation, Bourne, Mass.) to measure and record air temperature and RH during a drying process. The apparatus was used for positioning rough rice kernels inside the X-ray unit for imaging during the drying process.

Experimental procedure

Two drying experiments were conducted in this study, with each experiment comprising a series of drying runs at various combinations of temperature and RH. For experiment 1, drying was conducted using air at temperatures of 40°C, 50°C, or 60°C and RHs of 20%, 40%, or 60% followed by immediate tempering for 2 h at the drying air temperature; the experiment was conducted using a full factorial design. For each temperature and RH combination, drying was conducted from an initial rough rice MC of 17% to a final MC of 13%. The drying durations required to attain an MC of 13% MC were approximated using a thin-layer drying equation developed by Prakash and Siebenmorgen, (2018). Prior to the drying experiment, rough rice samples were scanned using the X-ray unit to select non-fissured kernels to be used for each
For each drying run, a sub-sample of 50 rough rice kernels were randomly selected from the non-fissured sample and were secured on the drying apparatus using double-sided adhesive tape (Double-sided adhesive, 3M Global Gateway, Maplewood, Minn.). During the drying process, an X-ray image was recorded at 3X magnification every 15 min during actual drying and thereafter at 0.5, 1, 2, 3, 4, 5, 7, 9, 12, 15, 18, 24, 36, and 48 h after actual drying; these images were used to determine the kinetics of fissure formation. The X-ray images were saved for later viewing to quantify the fissured kernel percentage (FKP) at each point during the drying process. The FKP was calculated as the number percentage of the kernels used for a drying run that were observed to have at least one visible fissure on an X-ray image.

For experiment 2, 50 rough rice kernels per drying run from a sample at 17% MC were dried for 30 min using a procedure similar to that aforementioned for experiment 1. The kernels were dried using air temperatures of 40°C, 50°C, or 60°C with RHs of 20%, 40%, or 60%, then tempered for 2 h at the drying air temperature. A fixed drying duration for all drying runs was used to simulate a commercial dryer in which each drying pass typically takes approx. 20-40 min (Schluterman and Siebenmorgen, 2004). The average MC of the 50 rice kernels was determined using the single-kernel moisture meter 48 h after drying and are shown in table 1. X-ray images were taken during drying, tempering, and subsequent storage to determine the kinetics of fissure formation in rice kernels during a 30-min drying duration. With sufficient tempering, it is expected that the fissures observed were those initiated during actual drying due to severe intra-kernel material state gradients (Schluterman and Siebenmorgen, 2007). The details of each drying run are shown in figure 1 and table 1.
RESULTS AND DISCUSSION

Fissured kernel percentages (FKPs) were determined on rough rice dried from 17% MC to 13% MC with heated air at 40, 50, or 60°C and RHs of 20, 40, or 60% then tempered at the drying air temperature for 2 h (Expt. 1), and on, rough rice dried for 30 min using heated air at 40°C, 50°C, or 60°C and RHs of 20%, 40%, or 60%, then tempered at the drying air temperature for 2 h (Expt. 2). As a point of clarity, the values of FKPs reported in figure 2 represent the percentage of fissured kernels detected using X-ray imaging at an indicated duration after active drying; these values thus inherently include all kernels that fissured during and after drying hence are cumulative. Conversely, the values of FKPs reported in figures 3 and 4 represent the percentage of kernels that fissured exclusively at an indicated stage of the drying process. Active drying is the period when there is actual moisture removal from rice kernels using heated air, i.e., when heated air is in direct contact with the kernels.

Fissuring kinetics

The fissures initiated in rough rice kernels did not all appear during active drying or immediately after active drying. A duration after completion of active drying was required for all fissures to appear and be detected using X-ray imaging. The number of fissured kernels were shown to increase rapidly during the initial 0-12 h after active drying. Few rough rice kernels had fissures appear during active drying but the majority of the kernels were shown to have fissures appear during tempering after completion of active drying. Generally, within 6 h after active drying, most fissures that were caused due to drying had appeared.

Effects of tempering

Figure 2 shows the fissuring kinetics of rough rice kernels. The first 2 h of the post-drying duration were the tempering duration. Tempering of kernels immediately after drying at
the drying air temperature allows for intra-kernel MC and material state gradients created during drying to subside, hence during subsequent cooling, the kernels transition to a glassy state as a uniform material, minimizing fissuring (Schluterman and Siebenmorgen, 2007). If drying is prolonged such that severe intra-kernel material state gradients are created during active drying, some kernels may fissure even when tempered for more than 2 h (Cnossen and Siebenmorgen, 2000). Similar observations were made in the current study wherein high-temperature, low-RH drying air conditions produced low equilibrium MCs (EMC) that caused portions of the kernel periphery to transition to a glassy state relative to the kernel core that remained in a rubbery state, resulting in severe intra-kernel material state gradients that caused kernel fissuring. Fissures in these kernels would be expected to form, regardless of the tempering treatment.

The FKPs were shown to reach a peak and plateau rapidly after active drying. This peak was reached almost exclusively during the 2-h tempering process, an indication that fissuring did not occur during cooling after kernels had been tempered. These findings confirm that if kernels do not fissure during active drying, adequate tempering will allow the MC and material state gradients within rice kernels to subside. Subsequently, intra-kernel material state gradients are less likely to be created during cooling, thereby minimizing fissuring. The fissures that appeared during tempering are proposed to have been caused by severe intra-kernel material state gradients during active drying. The fissuring kinetics of tempered samples help explain the HRY reductions reported by Schluterman and Siebenmorgen (2007). Such fissuring kinetics information was previously not available as fissure detection could only be done at the end of drying and tempering. This is because fissure detection was a destructive process that could only be determined on brown or milled rice kernels. The practical implication of the current study is that kernels dried under severe conditions in commercial dryers, then immediately held in
tempering bins may have fissures appear during the tempering period. Such fissures are proposed to be caused by the severe intra-kernel material state gradients created during active drying; however, these fissures require a duration to appear.

**Effects of drying air temperature and relative humidity**

Figure 2 shows the effects of drying air temperatures and RHs from experiment 1 on the fissuring kinetics of rough rice. There was an increase in FKPs with an increase in air temperature and a decrease in RH. This could be attributed to the increased drying rate as temperature was increased and RH decreased. An increase in the drying rate results in an increase in MC gradients that ultimately create severe intra-kernel material state gradients that can cause fissuring. Tempering has been shown to allow MC gradients created during drying to subside, hence during cooling, intra-kernel material state gradients are lessened, thereby minimizing fissure formation during cooling (Cnossen et al., 2003; Schluterman and Siebenmorgen, 2007). However, if fissures are caused during drying due to severe intra-kernel MC gradients, tempering may only prevent the formation of new fissures during cooling. This could explain why some fissuring occurred even on tempered samples.

Before this study was conducted, it was not well known when fissures appear in rough rice during the drying process, which includes active drying and subsequent tempering. Figure 3 shows the effect of drying air temperature and RH on the fissuring kinetics of rough rice samples from experiment 1. At high-temperature, low-RH air conditions such as at 60°C/20% RH and 60°C/40% RH, fissures appeared during active drying whereas, at low-temperature air conditions, fissures did not appear during active drying. This shows that if drying is conducted using harsh air conditions (≥60°C and ≤40% RH), severe intra-kernel material state gradients are created that cause the kernels to fissure instantaneously. On the other hand, less severe intra-
kernel material gradients may cause the kernels to fissure but the fissures appear later as shown in Figure 3. For both scenarios, even though the fissures may have been caused during active drying, most fissures appeared during the tempering period. Drying at 40°C and 50°C at 20%, 40%, or 60% RH is proposed to cause less severe intra-kernel material state gradients and thus could explain why for such air conditions, fissures did not appear during active drying. This indicates that between 50°C and 60°C, there exists a critical drying air temperature above which fissures will occur and will appear instantaneously during active drying, thus corroborating the findings of Arora et al., (1973) where this critical temperature was proposed to be approximately 53°C. The current study shows that the critical temperature may be dependent upon the RH of the drying air. At high-temperature, high-RH air conditions such as 60°C/60% RH, fissures did not appear during active drying. At such air conditions, severe intra-kernel material state gradients may have not been created thus the kernel fissures did not appear instantaneously.

In commercial cross-flow dryers, rice is typically dried using a multi-pass approach in which each drying pass results in approximately 20-40 min of rough rice exposure to heated air (Schluterman and Siebenmorgen, 2004). The drying runs for experiment 2, detailed in table 1, each resulted in rough rice being exposed to heated air for 30 min, followed by immediate tempering; thus, simulating a single drying pass in a commercial dryer. Figure 4 shows the effect of drying air temperature and RH on the fissuring kinetics of rough rice exposed to heated air for a 30-min drying duration followed by immediate tempering for 2 h at the drying air temperature. At high-temperature and low-RH air conditions, fissures appeared in rough rice kernels during active drying, tempering, and after tempering. At low-temperature drying air conditions such as 40°C and 50°C, fissures did not appear during active drying or after tempering except for the 50°C/20% RH air condition that had fissures appear after tempering. This shows that in high-
temperature and low-RH air conditions, fissures may appear instantaneously during drying while at low-temperature air conditions, a time delay is required before fissures appear. Similarly, for drying air conditions that cause severe intra-kernel material gradients (high-temperature, low-RH combinations), longer tempering durations may be required to allow intra-kernel material state and MC gradients to completely subside than for conditions that cause less severe intra-material state gradients (low-temperature, high-RH combinations). High-RH drying air conditions increase the EMC of the drying air thus decreasing the drying rate. The slow drying rate and high-EMC conditions minimized intra-kernel MC gradients and averted the creation of severe intra-kernel material state gradients leading to reduced fissure formation during drying and tempering. These findings corroborate those of Schluterman and Siebenmorgen (2007) and Ondier et al. (2012) wherein HRY increased with increased tempering durations.

**Fissure characterization**

Fissures in rice kernels can occur in various configurations and locations of a kernel. Figure 5 shows an X-ray image of rough rice kernels from a sample dried from 17% MC to 13% MC (experiment 1) using drying air at 60°C/20% RH. The fissures shown in figure 5 appeared during active drying. These fissures are of the transverse configuration i.e., perpendicular to the longitudinal axis of the kernel and originated from the surface of the kernel. Cnossen et al. (2003), described such fissures as surface cracks. It is believed that since the outer surface of the kernel loses moisture at a faster rate than the center portions, the kernel surface will experience tensile stress whereas the center portions will simultaneously experience compressive stress. If the tensile stress exceeds the tensile strength of the kernel, then fissures will initiate at the surface of the kernel.
Fissures that appear post-drying have different characteristics than those that appear during active drying. Figure 6 shows an X-ray image of rough rice kernels that were dried from 17% MC to 13% MC (experiment 1) using drying air at 60°C/20% RH. The arrows indicate the fissure locations on the kernels. The fissures that appeared during post-drying durations were perpendicular to the longitudinal axis of the kernel and are shown to have originated from the center portion of the kernel and increased in both length and width with increased post-drying durations, as shown in figure 6. It is proposed that severe intra-kernel material state gradients created during active drying causes stress within a kernel and a time interval is required for the stress created to build to a level that causes fissures to appear. For the drying air temperature (40°C, 50°C, and 60°C) and RH (20%, 40%, and 60%) combinations used in this study to dry rough rice from 17% MC to 13% MC (experiment 1), and from 17% MC for 30 min (experiment 2), the fissures observed were of the transverse configuration.

CONCLUSIONS

Experiments were conducted to determine the fissuring kinetics of rough rice at various drying air conditions; the following conclusions were drawn:

1. Harsh drying air conditions that result in severe intra-kernel material state gradients, typically high-temperature, low-RH combinations, cause fissuring to occur and appear instantaneously during active drying, whereas for mild drying conditions that result in less severe intra-kernel material state gradients, typically low-temperature and/or high-RH drying air conditions, a time interval after drying is required before fissures appear.

2. For both harsh and mild drying air conditions, the majority of fissures appear after active drying had ceased, typically during the tempering period.
3. Few kernels fissured after tempering, hence confirming that sufficient tempering of rice kernels immediately after active drying, greatly minimizes fissuring during post-drying cooling. However, longer tempering durations may be required for rough rice dried using high-temperature, low-RH drying air conditions.

4. The majority of fissures that appeared during active drying were shown to originate at the kernel surface, whereas fissures that appeared post-drying were shown to originate from the center of the kernel and moved outward perpendicular to the major kernel axis.

This study shows the role of temperature and RH on the kinetics of fissure formation during the drying process thus contributing information to the literature on when fissures appear during the rough rice drying process. Additionally, these findings guide rice drying researchers and practitioners on when to enumerate fissures in rough rice kernels, at least 12 h after active drying has ceased, to account for all kernels that might fissure due to the drying process. Similarly, these findings may be useful in optimizing drying processes and for modeling fissure formation in rough rice kernels which will be valuable for subsequent rice drying research.

ACKNOWLEDGMENTS

The authors acknowledge the financial support by the corporate sponsors of the University of Arkansas Rice Processing Program and the Arkansas Rice Research and Promotion Board. Additionally, of special acknowledgment, is the monetary support provided by the Kellogg Company for the purchase of the X-ray system.
FIGURES AND TABLES

Figure 1. Flow diagram and experimental layout of the study.

Long-grain rough rice lot (CLXL745) cleaned of material other than grain

500-g sample conditioned to 17% MC using air at 30°C/30% RH

Non-fissured 50-kernel rough rice samples dried to 13% MC (Expt. 1) and for 30 minutes (Expt. 2) at each of the 9 following drying air conditions

Drying air conditions

Temp

RH

40°C

80°C

60°C

20%, 40%, 60%

20%, 40%, 60%

20%, 40%, 60%

X-ray image saved every 15 minutes during actual drying

Kernels tempered at the respective drying air temperature for 2 hours, then cooled to ambient room temperature (22 ± 2°C)

X-ray images saved at 0.5, 1, 2, 3, 4, 5, 7, 9, 12, 15, 18, 24, 36, and 48 hours after drying

Fissured kernels counted on each of the saved X-ray images from every experimental combination
Figure 2. Effects of drying air temperature and relative humidity on the fissuring kinetics of rough rice kernels after drying rough rice from 17% MC to 13% MC (experiment 1), as detailed in Table 1. The samples were tempered for 2 h at the drying air temperature.
Figure 3. Effects of drying air temperature and relative humidity on the kinetics of fissure formation in rough rice kernels dried from 17% MC to 13% MC and tempered for 2 h at the drying air temperature immediately after drying (experiment 1).
Figure 4. Effects of drying air temperature and relative humidity on the kinetics of rough rice fissure formation during a 30-min drying duration from an initial moisture content of 17% and tempering for 2 h at the drying air temperature (experiment 2).
Figure 5. An X-ray image showing rice kernels observed during the drying process. The fissures appeared during active drying at 60°C/20% RH on the outer portion of the kernels. Arrows on the X-ray image indicate the location of the fissures.
Figure 6. X-ray images showing an individual rice kernel monitored after drying at 60°C/20% RH. The kernels were tempered for 2 h at the drying air temperature. The fissures were initiated at the center portion of the kernel during tempering and progressed outwards perpendicular to the major axis. Arrows on the X-ray images indicate the location of the fissure.
Table 1. Details of each drying run for experiments 1 and 2.

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REFERENCES


CHAPTER 2

VALIDATING THE GLASS TRANSITION HYPOTHESIS IN EXPLAINING FISSURE FORMATION IN ROUGH RICE KERNELS DURING THE DRYING PROCESS

Z. Odek, T. J. Siebenmorgen

ABSTRACT

Fissured rice kernels tend to break during milling, leading to milling yield reductions. A hypothesis involving glass transition/material state properties has been proposed to predict kernel fissuring during the drying process. The hypothesis has been used to explain fissuring during the drying process and has been supported by various milling studies. However, this hypothesis has not been validated from a fundamental fissuring standpoint. In this study, experiments were performed using drying air temperatures of 45°C, 50°C, 55°C, 60°C, and 65°C with RHs that produced equilibrium moisture contents (EMCs) of 6%, 8%, 10%, 12%, and 14%. These EMCs would position the kernel surface at select regions on a rice material state diagram during drying. At the end of active drying, kernels were tempered for 2 h at the drying air temperature. Fissures were viewed and detected in these kernels using X-ray imaging. Drying air temperature and EMC combinations that caused sufficient portions of the kernel surface to transition to the glassy region while the core remained in the rubbery region caused severe intra-kernel material state gradients. Such intra-kernel material state gradients caused severe fissuring thus supporting the glass transition hypothesis in explaining fissure formation. At drying air temperature and EMC combinations that did not cause severe intra-kernel material state gradients, severe fissuring was averted thus further supporting the glass transition hypothesis.

Keywords: State diagram, Material state, Rice quality, Tempering, X-ray imaging.
INTRODUCTION

Rice kernels with internal fractures of the endosperm, commonly referred to as fissures, tend to break during milling, leading to milling yield reductions. Fissured rice kernels are not only susceptible to breakage during milling, but also affect the functional properties of milled rice (Proctor and Goodman, 1985; Siebenmorgen et al., 2005; Mukhopadhyay and Siebenmorgen, 2017), causing end-use processors to incur significant financial losses (Siebenmorgen et al., 2009). Therefore, minimizing kernel fissuring is an important goal of the rice industry.

Fissuring caused by improper drying of kernels has been hypothesized to be a result of material state differences between the kernel periphery and the inner core, resulting in intra-kernel differential stress (Cnossen and Siebenmorgen, 2000). Such intra-kernel material state gradients are the result of temperature and moisture content (MC) differences within individual rice kernels generated during drying (Slade and Levin, 1995; Perdon et al., 2000). Cnossen et al. (2002) and Schluterman and Siebenmorgen (2007) proposed that rapid drying leads to large MC differences between the rice kernel surface and the core leading to intra-kernel material state gradients that cause hygrothermal stress.

Material state diagrams, such as that depicted in figure 1, can be used to predict the material states of rice kernels or portions of kernels at given temperatures and MCs. These material states in turn dictate the mechanical properties of kernels and position portions of kernels in either the glassy or rubbery region of a material state diagram. As indicated by the rice material state diagram developed by Siebenmorgen et al. (2004), rice kernels at a given MC exist as a glassy material if at a temperature below the glass transition temperature (Tg). By definition, kernels in the glassy state exhibit small expansion coefficients, specific volume, and diffusivity.
If the kernel temperature were increased above $T_g$, the kernel would transition from a glassy to a rubbery state and would exhibit greater expansion coefficients, specific volume, and diffusivity (Slade and Levine, 1995; Zeleznak and Hoseney, 1987).

Cnossen and Siebenmorgen (2000) and Perdon et al. (2000) presented a hypothesis, the glass transition hypothesis, which identifies the role of intra-kernel material state differences in causing fissures to form in rice kernels. Cnossen and Siebenmorgen (2000) hypothesized that fissuring of a rice kernel may be attributed to differential stress within the kernel exceeding the kernel material strength. These differential stresses are developed when sufficient portions of the kernel periphery transition to a glassy state while the kernel core remains in a rubbery state during drying. Fissuring can occur in two scenarios during the drying process according to this hypothesis. The first is during active drying as shown in figure 2. During high-temperature drying, a rice kernel will transition from a glassy state to a rubbery state as the kernel temperature approaches the drying air temperature. Subsequently, the surface layers of the kernel lose moisture at a faster rate than the core; hence, the surface layers, due to drying to a lesser MC, may transition back to a glassy state. The hypothesis proposes that if drying is prolonged such that sufficient portions of the kernel periphery (fig. 2; point S) transitions to a glassy state whereas the kernel core (fig. 2; point C) remains in a rubbery state, severe intra-kernel material state gradients will be created between the surface and the core, thereby causing stress. If this stress exceeds the kernel material strength, fissuring will be initiated.

The second scenario in which fissuring is hypothesized is after active drying i.e., during cooling without sufficient tempering, as shown in figure 3. During active drying, the intra-kernel material state gradients created may not be sufficiently severe to cause fissuring, however, the intra-kernel material state and MC gradients will still exist. If these gradients are not allowed to
subside, and the kernel is immediately cooled, the kernel surface and core will transition to the glassy state (fig. 3; point II) at different instances thus creating more severe intra-kernel material state gradients that could cause fissuring. Tempering was defined by Cnossen et al. (2001) as a holding process between drying passes that allows for MC and material state gradients generated within the kernel during drying to subside. Tempering immediately after a drying pass at the drying air temperature, i.e., point I in figure 3, allows moisture from the kernel core to diffuse to the outer layers of the kernel, therefore minimizing internal kernel stress that could cause fissuring (Li et al., 1999; Cnossen et al., 2002; Schluterman & Siebenmorgen, 2007; Aquerreta et al., 2007).

While laboratory milling studies have agreed with the hypothesis in explaining head rice yield reduction (Schluterman and Siebenmorgen, 2007; Ondier and Siebenmorgen, 2012), a comprehensive validation of this hypothesis from a fundamental fissuring standpoint was required. However, the inability to view and detect fissures in rough rice kernels during drying and tempering hindered validation efforts. With the addition of X-ray imaging equipment for fissure detection, such validation is now possible. Odek et al. (2018) used X-ray imaging to detect fissures in rough rice kernels during the drying process and showed the possibility of conducting in-situ drying research, which would be useful for validating the glass transition hypothesis. Thus, the goal of this study was to use X-ray imaging to validate the glass transition hypothesis in explaining rough rice fissuring due to active drying (fig. 2) using drying air conditions selected to allow different kernel portions to be at select regions of the rice material state diagram during active drying.
MATERIALS AND METHODS

Sample preparation

Long-grain rice of cultivar CL XL745 was harvested at 19% MC† near Stuttgart, Arkansas in 2017 and 18% MC near Pocahontas, Arkansas in 2018. Both lots were immediately cleaned using a dockage tester (XT4, Carter-Day Co., Minneapolis, Minn.) to remove material other than grain and stored in a cooler at 4°C until experiments were conducted. While the two rice lots were at 19% MC and 18% MC before storage, there was some reduction in MC during storage, producing rice lots at 17.9% MC and 16.7% MC, respectively, for the drying experiments. Three sub-lots were produced from these two lots, thus for the drying experiments, the samples used were at 16.7% MC and 17.9% MC in which some were dried to 16.7% MC.

Experimental setup

The test system comprised an environmental chamber (ESL 4CA Platinous Temperature and Humidity Chamber, Espec, Hudsonville, Mich.) that provided conditioned air for drying. The conditioned air was suctioned from the chamber using a fan (EcoPlus model 728459, Sunlight Supply, Inc., Vancouver, Wash.), then passed through an in-line heater (AHP-7561, Omega Engineering, Inc. Stamford, Conn.) that was controlled with a voltage regulator (3PN1010B, Staco Energy Products Co., Miamisburg, Ohio) to augment the environmental chamber in maintaining the desired drying air temperature. The conditioned air was ducted into an X-ray system (UltraFocus 60, Faxitron Bioptics LLC., Tucson, Ariz.) within which a drying apparatus (Odek et al., 2018) was positioned. The drying apparatus was equipped with a data logger (Hobo Pro V2 U23-002, Onset Computer Corporation, Bourne, Mass.) to measure and record air temperature and relative humidity (RH) during a drying process. The apparatus was

† All moisture content values are expressed on a wet basis.
used for positioning rough rice kernels inside the X-ray unit for imaging during the drying process.

**Experimental procedure**

Each drying run comprised placing 50 non-fissured rough rice kernels in the drying apparatus and passing drying air at a given temperature and RH over the kernels for a fixed 45-min drying duration. The drying conditions used were air temperatures of 45°C, 50°C, 55°C, 60°C, or 65°C with corresponding RHs that would result in drying air with equilibrium MCs (EMCs) of 6%, 8%, 10%, 12%, or 14% (fig. 4). Depending on the drying air temperature, each of these EMCs would position the kernel surface in either the glassy or the rubbery region of a material state diagram. At the end of each drying run, the kernels were tempered at the drying air temperature for 2 h. Tempering was conducted within the drying apparatus as described by Odek et al. (2018). Each drying run comprised an initial MC (3), a drying air temperature (5), and an EMC (5); each drying run combination was replicated four times, thus resulting in 300 drying runs (3×5×5×4). For each drying run, the percentage of fissured kernels was reported as an average of four drying replicates. The temperature and RH combinations that produced the aforementioned rough rice EMCs were determined using the modified Chung-Pfost equation (ASABE, 2012) and are detailed in table 1. A 45-min drying duration allowed the kernel periphery to dry to the rough rice EMC associated with the drying air while the kernel core remained at a relatively greater MC closer to the initial MC (IMC) of the kernel (Yang et al., 2002; Jia et al., 2002). Such scenarios would allow severe intra-kernel material state gradients to be created depending on the EMC of the drying air and the kernel IMC. As shown in figure 4, some drying air conditions would force the kernel surface to transition from a rubbery to a glassy phase during active drying while others will maintain the kernel surface and core exclusively in
the rubbery phase or glassy phase during active drying. During the drying process, X-ray images was taken before drying, at the end of active drying, and after tempering. These images were then used to quantify fissure formation for each of the selected drying conditions.

As depicted in figure 4, three factors can create intra-kernel material state gradients during active drying; the IMC of the rice, the rough rice EMC that is associated with the drying air, and the drying air temperature. On a material state diagram such as that in figure 4, the IMC determines the horizontal position of the kernel core, the drying air EMC determines the horizontal position of the kernel surface during active drying, and the drying air temperature determines the vertical position of both the kernel surface and core on a material state diagram. These three factors will be discussed in relation to fissure formation as predicted by the glass transition hypothesis, thus providing various scenarios that will be used to validate the hypothesis.

RESULTS AND DISCUSSION

Drying air temperatures, EMCs associated with the drying air conditions, and the percentage of fissured kernels resulting from the drying air conditions were superimposed on rice material state diagrams as shown in figure 5. Analogous to figure 4, the position of the kernel surface (denoted by *) and core (denoted by O) on the material state diagram during active drying corresponds to the EMC of the drying air and kernel IMC, respectively.

Drying air equilibrium moisture content

The rough rice EMC associated with the drying air is determined by the drying air temperature and RH. During active drying, the kernel surface quickly dries to the EMC of the drying air while the kernel core remains at a greater MC closer to the rough rice IMC (Yang et
al., 2002; Jia et al., 2002). Thus, as the EMC of the drying air is reduced, intra-kernel MC gradients will increase, which leads to an increase in intra-kernel material state gradients if the drying air temperature is one that allows a material state transition to occur. As depicted in figures 5 and 6, some drying air conditions caused the kernel surface to transition to a glassy region during active drying while other drying air conditions maintained the kernel surface in a rubbery region. The drying air conditions that caused the kernel surface to transition back to a glassy region during active drying caused fissuring due to the severe intra-kernel material state gradients created e.g., drying rice kernels at 65°C/10% EMC (fig. 5), resulted in 14.5% fissured kernels. On the contrary, when drying was conducted using air conditions that produced EMCs that maintained the kernel surface in a rubbery region, very few to no kernels fissured because severe intra-kernel material state gradients were averted e.g., drying rice kernels at 65°C/≥12% EMC (fig. 5).

In general, the percentage of fissured kernels increased markedly (fig. 5 & 6) when drying using air temperatures above the glass transition temperature and RHs that produced EMCs that caused the kernel surface to transition from a rubbery to a glassy phase during active drying. The point at which the percentage of fissured kernels increased markedly was shown to correspond to the temperature and EMC combinations that would cause a state transition on a rice material state diagram. For example, when drying rice at 16.7% MC (fig. 5) using air at 55°C, there was an 8 pp increase in the percentage of fissured kernels when the drying air EMC was decreased from 14% EMC (kernel surface remained in the rubbery region) to 12% EMC (kernel surface transitioned to the glassy region). Likewise, at 60°C, there was a 7.5 pp increase in the percentage of fissured kernels when the drying air EMC was decreased from 14% EMC to 12% EMC. Similarly, at 65°C, there was a 10.5 pp increase in the percentage of fissured kernels
when the drying air EMC was decreased from 12% EMC (kernel surface remained in the rubbery region) to 10% EMC (kernel surface transitioned to the glassy region). Similar trends were observed for rice at 16.7% MC (fig. 6a) and 17.9% MC (fig. 6b). These findings show that the position of a kernel surface relative to that of the kernel core on a rice material state diagram, along with the drying air temperature, determines whether a kernel will fissure during drying. These findings corroborate the glass transition hypothesis in explaining fissure formation during drying.

**Rough rice initial moisture content**

The IMC of rice can determine whether a kernel will exist in the glassy or rubbery region at the beginning of drying at a given drying air temperature. As MC increases, the glass transition temperature decreases (Perdon et al., 2000). As such, when drying using air temperatures above the Tg associated with the bulk IMC, the high-MC kernels in the rice lot will transition to a rubbery phase during drying while the low-MC kernels may remain in a glassy phase during drying. According to figure 6, for a given drying air temperature and drying air EMC, rice samples at 17.9% MC generally showed greater percentages of fissured kernels than samples at 16.7% MC. For example, when drying using air at 60°C/8% EMC, 13% of kernels fissured from the 17.9% MC while only 2.5% of kernels fissured from the 16.7% MC lot. Likewise, when drying using air at 65°C/10% EMC, 7% of kernels fissured from the 17.9% MC lot fissured while 0% of kernels fissured from the 16.7% MC lot. Similar trends were observed for all other drying air conditions (fig. 6). These findings show that high-MC rice is more susceptible to fissuring due to drying than low-MC rice. This can be explained using the glass transition hypothesis where for a given temperature and EMC combination, high-MC kernels are more likely to experience greater intra-kernel material state gradients than low-MC kernels. The
high MC-kernels will have greater differences in MC between the kernel surface i.e., drying air EMC and the core i.e., kernel IMC, than the low-MC kernels. These findings offer further validation of the glass transition hypothesis and corroborate the observations by Milner and Shellenberger (1953) in wheat kernels and Odek et al. (2018) in rice kernels where high-MC kernels were shown to be more susceptible to fissuring due to drying than low-MC kernels.

**Drying air temperature**

drying air temperature determines whether drying will take place in the glassy or rubbery region of a rice material state diagram. At drying air temperatures below the Tg, both the kernel surface and core will remain in the glassy region during drying. On the other hand, at drying air temperatures above the Tg, the kernel surface and core will exist in the rubbery region with a possibility of the surface transitioning to the glassy region depending on the drying air EMC.

Figure 7 shows the relationship between fissured kernels and the drying air temperature at various EMCs for rough rice samples at 16.7% IMC and 17.9% IMC. At drying air temperatures of 45°C, drying of rice lots at 16.7% IMC and 17.9% IMC either took place entirely in the glassy region (fig. 6a) or kernels barely transitioned into the rubbery region (fig. 6b). For these kernels, both the kernel surface and core were mostly below the glass transition line. As a result, severe intra-kernel material state gradients were not created, thus the kernels did not experience conditions that would cause fissuring according to the glass transition hypothesis. As the drying air temperature was increased to 50°C, lesser IMCs were required to cause drying to occur above the glass transition line due to the inverse relationship between temperature and MC on a rice material state diagram. Thus, some kernels within the 17.9% IMC lot transitioned into the rubbery region although, for the majority of kernels, drying took place entirely in the glassy region. This explains why at 45°C and 50°C (fig. 7), few or no kernel fissuring occurred because
these kernels were not exposed to conditions that would cause severe intra-kernel material state gradients that cause fissuring as predicted by the glass transition hypothesis.

As drying air temperatures were increased, the percentage of fissured kernels increased for drying air conditions that produced <10% EMC. For these EMCs, the percentage of fissured kernels greatly increased at drying air temperatures >55°C for rice at 16.7% MC, and at drying air temperatures ≥50°C for rice at 17.9% MC. These findings corroborate the glass transition hypothesis in that high-MC kernels have a lesser Tg than low-MC kernels. At drying air conditions that produced >10% EMC, an increase in the drying air temperature did not lead to an increase in the percentage of fissured kernels. This is because when drying using air conditions that produce >10% EMC, both the kernel surface and core remained in the glassy region at drying air temperatures ≤50°C or in the rubbery region at drying air temperatures ≥55°C (fig. 6). Thus, severe intra-kernel material state gradients that would result in kernel fissuring were averted. These findings support the existence of a critical drying air temperature above which the percentage of fissured kernels markedly increases. According to the current study, this critical drying air temperature is observed to be between 50°C and 55°C (fig. 7) thus corroborating the findings of Arora et al. (1973) wherein at temperatures above 53°C “the rate of expansion of rice kernels increased leading to an increase in the percentage of broken kernels.” However, kernel fissuring at drying air temperatures greater than this critical temperature will depend upon the drying air EMC and rice IMC, as explained by the glass transition hypothesis. These findings reinforce the observation of Odek et al. (2020) on kernel fissuring and head rice yield reduction in a lab-scale cross-flow dryer.

At drying air temperatures ≥55°C, as the drying air temperature was increased the percentage of fissured kernels increased. This was especially true at <10% EMC due to the
aforementioned role of the drying air EMCs on the position of the kernel periphery on a material state diagram. For example, for rice at 16.7% MC, drying using air at 6% EMC and temperatures of 55°C, 60°C, and 65°C led to an increase in the percentage of fissured kernels from 2.5% at 55°C, to 11% at 60°C, and to 33.5% at 65°C. Similarly, for rice at 17.9% MC, drying using air at 8% EMC and temperatures of 55°C, 60°C, and 65°C led to an increase in the percentage of fissured kernels from 5.5% at 55°C, to 13% at 60°C, and to 16.5% at 65°C.

The above findings corroborate the glass transition hypothesis and support its application in explaining fissure formation during active drying. The practical implication of this is that in commercial-scale rice dryers, where the drying air temperature can be controlled, the glass transition principles should be applied to minimize fissuring. This can be achieved by drying using air conditions that would cause the least amount of intra-kernel material state gradients as explained by the glass transition hypothesis.

CONCLUSIONS

The role of the glass transition hypothesis in explaining rice kernel fissuring during the drying process at various combinations of air temperatures (45°C, 50°C, 55°C, 60°C, and 65°C) and equilibrium moisture contents (EMCs) (6%, 8%, 10%, 12%, and 14%) was studied.

The rough rice EMC associated with the drying air determines the position of the kernel surface on a material state diagram during active drying. When the drying air EMC caused the kernel surface to transition back to a glassy state while the kernel surface remained in a rubbery state, there was severe fissuring of the kernels.

The rice initial moisture content (IMC) determines the position of the kernel surface on a material state diagram and thus the magnitude of intra-kernel material state gradients for a given
drying air EMC. High-MC kernels were likely to experience greater intra-kernel material state gradients and fissured more as compared to low-MC kernels that were likely to experience lesser intra-kernel material state gradients and fissured less.

The drying air temperature determines the vertical position of both the kernel surface and core on a material state diagram. At drying air temperatures between 50°C and 55°C, there was shown to be a critical temperature above which the percentage of fissured kernels markedly increased. This critical temperature was shown to be dependent upon the kernel IMC and drying air EMC. At air temperatures below this critical temperature, few to no kernels fissured during the drying process.

This study validates the glass transition hypothesis from a fundamental fissuring standpoint at various drying air conditions and supports the application of the hypothesis in minimizing kernel fissuring during the drying process.

ACKNOWLEDGMENTS

The authors acknowledge the financial support by the corporate sponsors of the University of Arkansas Rice Processing Program and the Arkansas Rice Research and Promotion Board. Additionally, of special acknowledgment, is the monetary support provided by Kellogg Company for the purchase of the X-ray system.
Figure 1. Brown rice material state diagram developed by Siebenmorgen et al. (2004) showing the relationship between glass transition temperature and kernel moisture content.
Figure 2. The hypothetical path followed by a rice kernel during prolonged, high-temperature, low-relative humidity drying. Surface (S), midpoint (M), and center (C) correspond to locations within a rice kernel.
Figure 3. Hypothetical tempering situations above and below the glass transition temperature (Tg) for a rice kernel dried using air temperatures above Tg. Surface (S), midpoint (M), and center (C) correspond to locations within a rice kernel (Adopted from Schluterman and Siebenmorgen, 2007).
Figure 4. Illustration of kernel surface positions (denoted by *) on a rice material state diagram as a result of the drying air temperatures and RHs shown in table 1, which would produce equilibrium moisture contents (EMCs) of 6%, 8%, 10%, 12%, or 14%. These drying air conditions would force the kernel surface to attain the EMC of the drying air thus the kernel surface would exist at select regions of a rice material state diagram during active drying whereas the core would be at or closer to the kernel IMC (denoted by O).
Figure 5. Position of a kernel periphery (denoted by *) as a result of a given drying air EMC, the core (denoted by O), and the associated fissured kernel percentage plotted onto a material state diagram when drying rice at an initial moisture content of 16.7%. The kernels were dried for 45 min at 45°C, 50°C, 55°C, 60°C, or 65°C, then tempered at the drying air temperature for 2 h. The fissured kernel percentages reported are an average of four drying runs with each drying run comprising 50 rough rice kernels.
Figure 6. Position of a kernel periphery (denoted by *) as a result of a given drying air EMC (denoted by *), the core (denoted by O), and the associated fissured kernel percentage plotted onto a material state diagram when drying rice at an initial moisture content of a) 16.7% and b) 17.9%. The kernels were dried for 45 min at 45°C, 50°C, 55°C, 60°C, or 65°C, then tempered at the drying air temperature for 2 h. The fissured kernel percentages reported are an average of four drying runs with each drying run comprising 50 rough rice kernels.
Figure 7. The proportion of fissured kernels at different drying air temperatures (45°C, 50°C, 55°C, 60°C, and 65°C) and equilibrium moisture contents (6%, 8%, 10%, 12%, and 14%) for rice lots at initial moisture contents of a) 16.7% and b) 17.9%. Each rough rice sample was dried for 45 min then tempered for 2 h at the drying air temperature.
Table 1. Drying air relative humidities estimated using the modified Chung-Pfost equation (ASABE, 2012) for air temperatures of 45°C, 50°C, 55°C, 60°C, and 65°C that would result in equilibrium moisture contents of 6%, 8%, 10%, 12%, and 14% for long-grain rough rice.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Equilibrium moisture content (% w.b.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>20% 34% 50% 64% 75%</td>
</tr>
<tr>
<td>50</td>
<td>22% 36% 52% 65% 76%</td>
</tr>
<tr>
<td>55</td>
<td>24% 39% 54% 67% 78%</td>
</tr>
<tr>
<td>60</td>
<td>26% 40% 55% 68% 79%</td>
</tr>
<tr>
<td>65</td>
<td>27% 42% 57% 70% 80%</td>
</tr>
</tbody>
</table>

The dimensionless constants A, B, and C of the modified Chung-Pfost equation were obtained from ASABE Standards (ASAE D245.6).
REFERENCES


CHAPTER 3

EFFECT OF POST-DRYING TEMPERING OF RICE ON MINIMIZING KERNEL
FISSURING AND MAXIMIZING MOISTURE REMOVAL

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ABSTRACT

Improper rice drying results in kernel fissuring, leading to head rice yield reduction due to breakage during milling. The objective of this study was to determine the percentage points (pp) of moisture content reduction that can be achieved in a drying pass without significantly fissuring kernels. Long-grain rough rice of cultivars CL XL745 and Diamond at initial moisture contents of 18%, 17%, 16%, 15%, and 14% were dried using air at 45°C/20% relative humidity (RH), 50°C/15% RH, 55°C/12% RH, 60°C/10% RH, and 65°C/8% RH to moisture contents of 17%, 16%, 15%, 14%, 13%, and/or 12% with and without post-drying tempering. Tempering was conducted at the drying air temperature for 4 h. The resulting samples achieved between 1 and 7 pp of moisture content reduction in a single drying pass. The pp of moisture content reduction that can be attained in a single drying pass without causing significant fissuring varied across the cultivars tested. Generally, ~2 pp of moisture content reduction was achieved in a single pass drying for CL XL745 and ~4 pp for Diamond without causing adverse fissuring when samples were not tempered after drying. However, with tempering, ~3.5 pp of moisture content reduction was achieved in a single drying pass for CL XL745 and ~5.5 pp for Diamond without causing significant fissuring. However, these amounts varied depending on the drying air conditions and rice initial moisture content. For both CL XL745 and Diamond rice cultivars, tempering immediately after drying reduced the fissured kernel percentage by up to half of that
when the kernels were not tempered. These findings quantify the importance of rice tempering and provide information on how much moisture can be safely removed in a single drying pass. Such findings may be applied to different dryer types to reduce fissuring due to drying hence minimizing head rice yield reductions.

**Keywords:** Glass transition, Moisture content reduction, Rice quality, Single-pass drying, X-ray imaging.

**INTRODUCTION**

Rice is typically harvested in the U.S. mid-South at moisture contents (MC)® ranging between 14% and 25% then dried to between 12% and 14% MC for safe storage and subsequent milling. During high-temperature drying, rice kernels tend to fissure thus leading to milling yield reductions (Kunze, 1979; Schluterman and Siebenmorgen, 2007; Odek et al., 2017). Low drying air temperatures have been used in rice drying to minimize kernel fissuring and breakage during subsequent milling (Bonazizi et al., 1997; Ondier et al., 2010; Kim et al., 2013). However, due to the long drying durations associated with low-temperature drying, the use of low drying air temperatures may not be practical for most commercial rice drying facilities (Ondier et al., 2012).

Maximizing dryer throughput is desirable from a logistical standpoint (Walker and Bakker-Arkema, 1981) thus, high drying air temperatures are typically used to dry rice in commercial cross-flow systems (Schluterman and Siebenmorgen, 2004). Schluterman and Siebenmorgen (2004) and Odek et al. (2020) reported that the samples located closer to the

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® All moisture content values are expressed on a wet basis.
heated-air plenum experience greater kernel fissuring and head rice yield reductions (HRYR) than sample located further from the heated-air plenum.

Cnossen and Siebenmorgen (2000) presented a hypothesis, the glass transition hypothesis, that explains rice fissuring during active drying and tempering. The hypothesis proposes that prolonged drying causes a sufficient volume of the kernel periphery to transition to a glassy state relative to the rubbery core leading to intra-kernel material state differences that cause fissuring. The glass transition hypothesis has been supported by various laboratory milling studies (Schluterman and Siebenmorgen, 2007; Ondier and Siebenmorgen, 2012; Mukhopadhyay et al., 2019) and has been validated in explaining fissure formation during drying (Odek and Siebenmorgen, 2020).

Tempering was defined by Cnossen et al. (2001) as a holding step between drying passes that allows for MC and material state gradients generated within rice kernels during active drying to subside. Various laboratory experiments have shown that tempering rice kernels immediately after drying can reduce kernel fissuring and minimize HRYR (Cnossen and Siebenmorgen, 2000; Cnossen et al., 2003; Aquerreta et al., 2007; Schluterman and Siebenmorgen, 2007; Mukhopadhyay et al., 2019). However, the benefit of rice tempering on minimizing kernel fissuring at various drying air conditions has not been numerically quantified, specifically in terms of the amount of moisture that can be removed in a single drying pass without significantly causing fissuring; a metric that may be valuable for maximizing dryer throughput. Thus, the objective of this study was to identify the maximum percentage points (pp) of MC (PPMC) reduction that can be achieved in a single drying pass for tempered rice samples versus for non-tempered (immediately naturally cooled) rice samples without causing significant kernel fissuring.
MATERIALS AND METHODS

Sample preparation

Long-grain rice of cultivars CL XL745 and Diamond were harvested at 18% MC near Pocahontas, Arkansas in September 2018. Both rice lots were immediately cleaned using a dockage tester (XT4, Carter-Day Co., Minneapolis, Minn.) to remove material other than grain. The rice lots were then conditioned to produce sub-lots at 18%, 17%, 16%, 15%, and 14% MC using drying air at 30°C / 30% RH. Sample MC was determined by drying 15 g of rough rice for 24 h at 130°C in a convection oven (Jindal and Siebenmorgen, 1987)

Experimental procedure

Drying experiments were conducted using drying air at temperatures of 45°C, 50°C, 55°C, 60°C, and 65°C with corresponding RHs that would result in a humidity ratio of 0.012 kg water kg\(^{-1}\) dry air; this humidity ratio is typical for ambient air during the rice drying season in the U.S mid-South. For a rice sample at 18% MC, six sub-samples of approximately 50 g were placed in six trays (230 mm × 100 mm × 45 mm). The six sub-samples were placed in an environmental chamber (ESL 4CA Platinous Temperature and Humidity Chamber, Espec, Hudsonville, Mich.) set at a specified temperature (e.g. 65°C) and corresponding RH (fig. 1). The chamber is capable of maintaining temperature in the range of -35°C to 150°C (±0.5°C) and RH in the range of 6% to 98% (±2.5%) at an airflow rate of 0.38 m\(^3\) s\(^{-1}\) m\(^{-2}\). Each of the six sub-samples were dried to either 17%, 16%, 15%, 14%, 13%, or 12% MC. Immediately after drying, the rough rice from the six trays were each divided into two portions. One portion was immediately placed in sealed plastic bags and tempered for 4 h at the drying air temperature while the remaining portion was allowed to cool at room temperature (22°C±1°C). The above procedure was repeated for the remaining samples at each IMC (17%, 16%, 15%, and 14%) then
for the remaining drying air temperatures (60°C, 55°C, 50°C, and 45°C). The entire drying procedure was replicated and then the whole procedure repeated for the other rice cultivar. A summary of the layout is shown in figure 1.

After drying was complete, the rough rice sub-samples were stored in sealed plastic bags for at least 48 h then fissure detection and enumeration were conducted using an X-ray system (UltraFocus 60, Faxitron Bioptics LLC, Tucson, Ariz.). For fissure detection, 100 rough rice kernels of each sub-sample were scanned and the X-ray images were saved for fissure enumeration.

Statistical analyses

Statistical analyses were conducted using JMP Pro statistical software (ver. 15.2.0, SAS Institute, Cary, N.C.). The Generalized Regression platform was used to fit a second order response with a lognormal distribution. Forward selection with AICc validation method was used to model and predict the FKPs utilizing as inputs to determine the relationships between cultivar, drying air conditions, IMC, pp of MC reduction, and post-drying treatment. For each cultivar lot, predicted contour profilers based on the selected final model were utilized to determine drying combinations that would result in the least number of fissured kernels in a single drying pass.

RESULTS AND DISCUSSION

It is important to note that reporting changes in MC can often be misleading and/or difficult to interpret when the term “percent” is used (Prakash and Siebenmorgen, 2019). For instance, when drying rice at 19% MC to 14% MC, the change in MC is 26.3%; referring to this as a 5% change would be inaccurate. Thus, the term “percentage points” is used to avoid such inaccurate and confusing interpretations (Siebenmorgen et al., 2005). The above example would
thus be more accurate and easier to interpret if the change in MC is reported as a 5 percentage point reduction.

Table 1 shows the variable of importance report. This report contains indices that measure the important factors in a model, independently of the model type and fitting method. It then estimates the variability in the predicted response (FKP) based on a range of variations for each factor. If varying a factor causes the greatest variability in the response FKP, then that factor is of greater importance. The variable of importance report shows that the pp of moisture removed is the most important factor, followed by cultivar then post-drying treatment, drying air temperature, and IMC, respectively. The main effects for the variables pp of moisture removed, cultivar, post-drying treatment, drying air temperature, and IMC were 0.422, 0.310, 0.033, 0.010, and 0.009, respectively. These main effects contributed the most to the total effects (0.622, 0.455, 0.104, 0.031, and 0.019, respectively). These findings are plausible because the kernel surface dries at a faster rate than the kernel core. Thus, when greater pp of moisture is removed in a single drying pass, greater and more severe intra-kernel material state gradients will be created that result in significant kernel fissuring. These findings support previous studies that have proposed a multi-pass drying approach to minimize the amount of moisture removal in a single drying pass, hence minimizing milling yield reductions (Benny & Basil, 1970). Therefore, it is recommended that a certain pp of MC reduction is not exceeded in a single drying pass to minimize kernels fissuring. This study comprised a series of experiments to elucidate the maximum pp of moisture that can be safely removed and is discussed in the subsequent sections.

Contour profilers are plots of predicted response contours that allow for the visualization of multiple factors simultaneously. Based on a correlation equation developed by Odek et al. (2017) a 1 pp increase in FKP results in a 0.6 pp decrease in HRY. Therefore, a 5 pp decrease in
HRY is equivalent to approx. 8.3 pp increase in FKPs. For the current study, the rice lots had FKPs of 13.5% and 6.8% for CL XL745 and Diamond, respectively, before drying (control). As such, an FKP increase of <8.3 pp from the control was considered to be within an acceptable limit. An upper limit for FKPs was set at 21.8% (13.5%+8.3 pp) and 15.1% (6.8%+8.3 pp) for CL XL745 and Diamond, respectively. The unshaded areas of the contour profiler plots shown in Figures 2 and 3 represent the acceptable FKP ranges for various combinations of cultivar, drying air conditions, IMC, pp of MC reduction, and post-drying treatment.

Effect of tempering on maximizing moisture removal

Greater moisture can be removed from rice kernels in a single drying pass without causing significant fissuring when the samples are tempered than when not tempered. Figures 2 & 3 show the effect of tempering on the percentage points of moisture removal in a single drying pass without significantly causing fissuring for CL XL745 and Diamond rice samples, respectively. The pp of MC reduction could be achieved in a single pass without causing the FKPs to significantly exceed that of the control samples varied depending on the rice cultivar, rice IMC, and drying air conditions.

Generally, for CL XL745 (fig. 2) at all drying air conditions without tempering, for samples at 18% MC and 17% MC, approximately 2.5-3 pp of MC reduction could be achieved in a single drying pass without adversely causing fissuring. For the samples at 16% MC and 15% MC, approximately 2-2.5 pp of MC reduction, and for samples at 14% MC approximately 1.5-2 pp of MC reduction could be achieved in a single drying pass without adversely causing fissuring. With sufficient tempering, there was an increase in the pp of MC reduction that could be achieved in a single drying pass. Generally, for samples at 18% MC, 17% MC, and 16% MC, approximately 3.5-4 pp of MC reduction could be achieved in a single drying pass without
adversely causing fissuring. For samples at 15% MC approximately 3-3.5 pp MC reduction, and for samples at 14% MC approximately 2.5-3.5 pp of MC reduction could be achieved in a single drying pass without adversely causing fissuring.

For Diamond (fig. 3), at all drying air conditions without tempering, for samples at 18% MC, 17% MC, and 16% MC, approximately 4-5 pp of MC reduction could be achieved in a single drying pass without adversely causing fissuring. For samples at 15% MC approximately 3.5-5 pp MC reduction, and for samples at 14% MC, approximately 3-4.5 pp of MC reduction could be achieved in a single drying pass without adversely causing fissuring. With sufficient tempering, there was an increase in the pp of MC reduction that could be achieved in a single drying pass. Generally, for samples at 18% MC, 17% MC, and 16% MC, approximately 5.5-6 pp of MC reduction could be achieved in a single drying pass without adversely causing fissuring. For samples at 15% MC approximately 5-6 pp of MC reduction, and for samples at 14% MC, approximately 4.5-6 pp of MC reduction could be achieved in a single drying pass without adversely causing fissuring.

These findings show that to avoid significant fissuring due to drying, there is an upper limit to the pp of MC reduction that can be achieved in a single drying pass. It is proposed that when the aforementioned pp of MC reduction limit is exceeded during drying, intra-kernel MC gradients and the resulting intra-kernel material state gradients may have greatly increased thus creating stresses within the kernels that results in material failure and fissure initiation (Schluterman and Siebenmorgen, 2007).

The pp of MC reduction that could be safely achieved in a single drying pass increased with an increase in rice IMC. For example, when drying Diamond samples using air at 60°C with sufficient tempering, 5.7 pp of MC reduction was achieved for samples at 18% IMC, 5.4 pp of
MC reduction for samples at 16% IMC, and 4.6 pp of MC reduction for samples at 14% IMC. Similar observations were made by Schluterman and Siebenmorgen (2007) wherein, when drying Francis rice samples using air at 60°C/17% RH followed by 90 min of tempering, 4.8 pp and 4.2 pp of MC reduction was achieved in a single drying pass without affecting head rice yield for rice lots at 19.5% MC and 17.4% MC, respectively. It is proposed that during drying using air temperatures above the glass transition temperature, high-MC kernels are positioned further from the glass transition line than low-MC kernels and as such, greater amounts of moisture can be removed from the high-MC kernels before sufficient portions of the kernel periphery transition into the glassy phase.

Drying air temperature was shown to have a more significant effect on the pp of MC reduction that can be achieved in a single drying pass without causing fissuring for Diamond than for CL XL745. Air temperatures of 45°C and 50°C allowed more moisture to be removed in a single drying pass without causing significant fissuring than at air temperatures of 55°C, 60°C, and 65°C. These findings corroborate previous studies that have shown 50°C-55°C to be a critical drying air temperature range above which kernel fissuring increases due to the intra-kernel material state gradients created. Based on the sample IMCs evaluated, most of the kernels remained in a glassy material state when drying using air temperatures below 50°C; thus, severe intra-kernel material state gradients that cause fissuring were averted (Odek & Siebenmorgen, 2020).

**Effect of tempering on minimizing kernel fissuring**

Tempering rice kernels immediately after drying allows the intra-kernel MC and material state gradients created during drying to subside, thus minimizing kernel fissuring during subsequent cooling. Figures 2 and 3 show contour profiler plots of CL XL745 and Diamond,
respectively. The contour profilers show the FKP at various IMC, drying air temperature, pp of moisture removed, and post-drying treatment combinations. These contour profilers can be used to compare the FKP of a treated sample to a control sample thus showing the pp increase in FKP due to a given treatment combination. At high-temperature high-IMC combinations, drying CL XL745 samples at 18% MC to 12.5% MC in a single drying pass using air temperatures of 65°C resulted in a 51 pp increase in the FKP from that of the control when the kernels were not tempered. When tempered, there was a 21.7 pp increase in the FKP from that of the control. On the other hand, at high-temperature low-IMC combinations, drying CL XL745 samples at 14% MC to 12.5% MC in a single drying pass using air at 65°C resulted in a 4.7 pp increase in the FKP when kernels were not tempered. When tempered, there was a 1.5 pp increase in the FKP from that of the control.

Similarly, at low-temperature high-IMC combinations, drying CL XL745 samples at 18% MC to 12.5% MC in a single drying pass using air at 45°C resulted in a 37.7 pp increase in the FKP when kernels were not tempered and a 17.5 pp increase in the FKP from that of the control when tempered. On the other hand, at low-temperature low-IMC combinations, drying CL XL745 rice samples at 14% MC to 12.5% MC in a single pass using air at 45°C resulted in a 5.9 pp increase in the FKP when the kernels were not tempered and a 4.1 pp increase in the FKP from that of the control when tempered.

Diamond rice samples were consistently less susceptible to fissuring than CL XL745 rice samples when exposed to identical drying conditions. For high-temperature high-IMC combinations, drying Diamond samples at 18% MC to 12.5% MC in a single drying pass using air temperatures of 65°C resulted in a 17.0 pp increase in the FKP when the kernels were not tempered. When tempered, there was a 6.8 pp increase in the FKP from that of the control. On
the other hand, for high-temperature low-IMC combinations, drying Diamond samples at 14% MC to 12.5% MC in a single drying pass using air at 65°C resulted in a 2.5 pp increase in the FKP when kernels were not tempered. When tempered, there was a 1.1 pp increase in the FKP from that of the control.

Similarly, for low-temperature high-IMC combinations, drying Diamond samples at 18% MC to 12.5% MC in a single drying pass using air at 45°C resulted in an 8.7 pp increase in the FKP when kernels were not tempered and a 3.0 pp increase in the FKP when tempered. On the other hand, for low-temperature low-IMC combinations, drying Diamond rice samples at 14% MC to 12.5% MC in a single pass using air at 45°C resulted in a 1.3 pp increase in the FKP when the kernels were not tempered and a 0.9 pp increase in the FKP from that of the control when tempered.

These results show that tempering of rice kernels immediately after drying can reduce the FKP by up to half of that when kernels are immediately cooled without tempering. In other words, if kernels are not tempered immediately after drying and are allowed to cool, up to 50% of the resulting fissuring can be attributed to the intra-kernel material state gradients. These gradients are created when the kernel periphery and core transition from a rubbery state to a glassy state at different instances during cooling leading to material stress. The remaining percentage of fissuring can be attributed to intra-kernel material state gradients created during active drying when sufficient portions of the kernel periphery transition to a glassy phase while the core remains in a rubbery phase (Schluterman and Siebenmorgen, 2007). Severe intra-kernel material state gradients created during active drying would still cause fissuring regardless of the post-drying treatment. Odek et al. (2020) reported that in such cases, tempering may only prevent the formation of new fissures during cooling, thus explaining why fissuring occurred
even on samples that were tempered immediately after drying. Such fissuring can be minimized by drying using air conditions that do not cause a transition of a kernel surface to a glassy state while maintaining the core in a rubbery state as described by the glass transition hypothesis (Cnossen & Siebenmorgen, 2002; Perdon et al., 2002; Odek & Siebenmorgen, 2020).

Figure 4 shows the effect of post-drying treatments on the FKPs of rice kernels of different cultivars at different IMCs and dried using different drying air conditions. As the drying air temperature was increased, the difference in FKPs between tempered and non-tempered (immediately cooled) samples increased. Similarly, as the IMC increased, the difference in FKPs between tempered and non-tempered samples increased. The differences were greater for CL XL745 than for Diamond for both drying air temperature and IMC. For CL XL745, the differences in FKPs became more apparent at IMCs >15% and drying air temperatures ≥50°C. On the other hand, for Diamond, the differences in FKPs became more apparent at IMCs >16% and drying air temperatures ≥55°C. These findings corroborate the glass transition hypothesis in that at approximately ≤15% IMC and <50°C or ≤16% IMC and <55°C, a majority of kernels may have remained in the glassy region during drying (Siebenmorgen et al., 2004; Odek & Siebenmorgen, 2020). As such, intra-kernel material state gradients were averted, and thus both tempered and non-tempered samples were expected to have almost similar FKPs.

CONCLUSIONS

Experiments were conducted using rice samples of two cultivars (CL XL745 and Diamond) at varying initial MCs (14%, 15%, 16%, 17%, and 18%), which were dried to various MCs (12%, 13%, 14%, 15%, 16%, and 17%) using various drying air conditions (45°C/20% RH, 50°C/15% RH, 55°C/12% RH, 60°C/10% RH, and 65°C/8% RH) that result in a humidity ratio.
of 0.012 kg water kg$^{-1}$ dry air. After drying was completed, each sample was exposed to post-drying treatments (tempering for 4 h and no tempering).

The fissured kernel percentages (FKPs) of rough rice dried in a single pass were affected by the rice cultivar, initial MC, drying air conditions, post-drying treatment, and the percentage points (pp) of MC reduction. Generally, cultivar CL XL745 exhibited greater FKPs than Diamond under identical IMCs and drying air conditions. Post-drying treatments affected the pp of MC that could be safely removed from rice samples in a single drying pass. Tempering samples at the drying air temperature for 4 h made it possible to remove ~3.5 pp of MC in a single pass for CL XL745 and ~5.5 pp of MC in a single pass for Diamond without significantly fissuring the kernels. For samples that were not tempered immediately after drying, lesser pp of MC could be removed from the samples in a single pass without causing significant kernel fissuring. Approximately 2 pp of MC reduction could be achieved for CL XL745 and ~4 pp of MC for Diamond for the non-tempered samples. If these limits are not exceeded in a single drying pass, fissuring due to drying could be significantly reduced and HRY reductions minimized. For the drying air conditions, initial MCs, and pp of moisture removed that were evaluated in this study, tempering of rice kernels immediately after drying reduced the FKP by up to half of that when kernels were not tempered. This study provides numeric quantification of the relative importance of tempering rice kernels after drying on FKPs and pp of MC reduction that can be safely achieved in a single drying pass. These findings can be applied to different dryer types to minimize kernel fissuring and maximize dryer throughput.
ACKNOWLEDGEMENTS

The authors acknowledge the financial support by the corporate sponsors of the University of Arkansas Rice Processing Program and the Arkansas Rice Research and Promotion Board.
FIGURES AND TABLES

![Experimental layout showing drying air temperatures (45°C, 50°C, 55°C, 60°C, or 65°C) and the corresponding RHs (20%, 15%, 12%, 10%, and 8%, respectively) that would result in a humidity ratio of 0.012 kg water kg$^{-1}$ dry air used to dry rough rice from various initial moisture contents (18%, 17%, 16%, 15%, or 14%) to various final moisture contents (17%, 16%, 15%, 14%, 13%, or 12%). Two drying replications were conducted for each cultivar lot.](image-url)

Figure 1. Experimental layout showing drying air temperatures (45°C, 50°C, 55°C, 60°C, or 65°C) and the corresponding RHs (20%, 15%, 12%, 10%, and 8%, respectively) that would result in a humidity ratio of 0.012 kg water kg$^{-1}$ dry air used to dry rough rice from various initial moisture contents (18%, 17%, 16%, 15%, or 14%) to various final moisture contents (17%, 16%, 15%, 14%, 13%, or 12%). Two drying replications were conducted for each cultivar lot.
Figure 2. Contour profiler plots showing the effect of post-drying treatment on the percentage points (pp) of moisture content reduction in a single drying pass without significantly increasing the fissured kernel percentage for CL XL745 rough rice at various initial moisture contents and drying air conditions. The contours represent fissured kernel percentages at a 5-pp increment.

The rice lot had an average of 13.5% fissured kernels before drying.
Figure 3. Contour profiler plots showing the effect of post-drying tempering on the percentage points (pp) of moisture content reduction in a single drying pass without significantly increasing the fissured kernel percentage for Diamond rough rice at various initial moisture contents and drying air conditions. The contours represent fissured kernel percentages at a 5-pp increment. The rice lot had an average of 6.8% fissured kernels before drying.
Figure 4. Effect of post-drying treatment on the fissured kernel percentage of CL XL745 and Diamond rice cultivars at various initial moisture contents, drying air conditions, and varying amounts of moisture removed in a single drying pass.
Table 1. Effect of experimental variables on the percentage of fissured kernels due to the drying process.

<table>
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<tr>
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REFERENCES


CHAPTER 4

EFFECT OF GRAIN INVERTERS IN CROSS-FLOW DRYERS ON KERNEL FISSURING AND HEAD RICE YIELD REDUCTION

Z. Odek, B. Prakash, T. J. Siebenmorgen

ABSTRACT

Industrial-scale cross-flow dryers are commonly equipped with grain inverters to facilitate uniform drying across the column thickness, but limited information is available on the effect of grain inverters on rice milling quality. In this study, lab-scale drying experiments were performed to investigate the effect of grain inverters on kernel fissuring and head rice yield reduction. Rice samples of long-grain cultivar Roy J were dried for 60 min at plenum air temperatures of 45°C, 50°C, 55°C, and 60°C. The number of grain inversions during a 60 min drying period were 0, 1, and 2. After drying, a portion of the sample was tempered at a final bulk-rice temperature (heated tempering), while the other portion was tempered at ambient room temperature (ambient tempering). At plenum air temperatures of 55°C or 60°C, grain inversion (1 or 2 inversions) minimized fissuring of kernels closest to the heated-air plenum compared to 0 grain inversion. At 45°C and 50°C, grain inversion did not affect kernel fissuring. Similarly, at plenum air temperatures greater than 55°C for both ambient tempering and heated tempering approaches, 1 or 2 grain inversions significantly minimized head rice yield reductions compared to 0 grain inversion. These findings may be valuable for designing cross-flow dryers by informing decisions on the number of grain inverters needed to reduce fissuring and minimize head rice yield reduction.

Keywords: Column dryer, Milling yields, Reversed airflow, Rice quality, Tempering, Turnflow, X-ray imaging.
INTRODUCTION

Dryers of various configurations are used to dry rough rice across the world. In the U.S., cross-flow column dryers are the most popular type of rice dryer at the industrial scale (Rumsey and Rovedo, 2001; Schluterman and Siebenmorgen, 2004). In such dryers, grain flows vertically downward between perforated metallic screens, forming grain columns (fig. 1a). Heated air flows through the grain columns in a direction perpendicular to that of the grain movement; therefore, such dryers are called cross-flow dryers. In this article, “rice” refers to rough rice (paddy), the unhulled form of the crop, unless specified otherwise.

In cross-flow dryers, rice kernels at different locations across the column thickness dry at different rates due to drastically different drying air conditions across the column. Rice kernels closer to the heated-air plenum interact with hotter air and dry faster than kernels farther away from the plenum; those kernels interact with cooler, more humid air. Due to these differences in drying rates, moisture content (MC) differences tend to occur across the drying column. Prakash et al. (2017) observed that the MC difference in rice across a column can be as much as 3.6 percentage points (w.b.). Such non-uniformity within cross-flow dryers can cause under- or over-drying of rice and fissuring of kernels, which can reduce head rice yield (HRY). Head rice yield (USDA, 2009) is a quality parameter representing the mass fraction of rough rice that remains as intact kernels, or head rice, after milling to remove hulls and bran. Fissuring of kernels is a major cause of HRY reduction (HRYR). To improve uniformity in drying, industrial-scale cross-flow dryers are often equipped with grain inverters (also called turnflows or grain exchangers), which reverse the position of kernels in the column with respect to the flow of drying air (fig. 1b). Alternatively, the actions of a grain inverter can be thought of as dividing a dryer column into
several vertical sections; grain inverters produce a similar effect on the uniformity of drying as that of reversing the direction of airflow in each section. (fig. 1c).

While several authors have investigated the use of cross-flow grain dryers (Thompson et al., 1968; Otten et al., 1980; Brooker et al., 1992; Bakker-Arkema and Liu, 1997; Rumsey and Rovedo, 2001), only a few studies have considered the operation of grain inverters (Paulsen and Thompson, 1973; Khatchatourian et al., 2013; Nguyen et al., 2016; Prakash and Siebenmorgen, 2018). None of those studies investigated the role of grain inversions on kernel fissuring and HRYR. The current study follows a previous study (Prakash and Siebenmorgen, 2018) that described the development of a mathematical model to simulate rice dryers with grain inverters. The goal of the study described herein was to examine the role of grain inversions on rice quality attributes, specifically rice kernel fissuring and HRYR. Experiments were performed to simulate grain inversions (0, 1, or 2) in a laboratory-scale dryer that was operated at drying temperatures of 45°C, 50°C, 55°C, and 60°C. Fissured kernels were enumerated at six locations across the grain column, while HRY was determined on the bulk rice sample from the drying column.

MATERIALS AND METHODS

Rice samples

Rice of long-grain cultivar Roy J was harvested at approximately 19% MC (w.b.) in September 2018 at the University of Arkansas Rice Research and Extension Center near Stuttgart, Arkansas. The rice was cleaned using a dockage tester (XT4, Carter-Day, Minneapolis, Minn.) to remove foreign material and unfilled kernels, and then stored at approximately 4°C in plastic containers prior to the drying experiments. While all rice used in this study was from the same lot, there were slight MC changes during storage, producing slightly different initial MCs for the drying experiments.
Laboratory dryer

The conceptual equivalence between a continuous-flow, cross-flow dryer and a stationary-bed dryer has been reported (Prakash et al., 2017), and simulations of cross-flow drying using a laboratory-scale, stationary-bed dryer have been performed (Prakash and Siebenmorgen, 2018). In this study, a similar laboratory dryer setup was used, as shown in figure 2.

Drying air of a desired temperature and RH was produced by a 0.91 m³ controlled-environment chamber (ESL 4CA Platinous Temperature and Humidity Chamber, ESPEC, Hudsonville, Mich.). The chamber is capable of maintaining temperature in the range of -35°C to 150°C (±0.5°C) and RH in the range of 6% to 98% (±2.5%). A 0.56 kW centrifugal fan (Dayton Electric, Chicago, Ill.) that was mounted outside the chamber to avoid high-temperature exposure, suctioned air via an insulated air duct from the chamber, and forced it through the grain in the drying column located inside the environmental chamber (fig. 2a).

The dryer assembly, which was placed inside the environmental chamber, comprised a wooden box and a cylindrical acrylic-glass sample holder that served as the drying column. The wooden box served as a plenum, and the air properties therein were measured to represent the inlet air conditions to the rice column. The sample holder comprised the acrylic cylinder, which contained the rice, and two detachable components: a perforated metallic disc and flange that fit into the bottom of the cylinder, and a top component that resembled the bottom component (fig. 2c).

During a drying experiment, rice was first placed in the sample holder, and then the top component was placed inside the top of the cylinder and secured using two screw knobs located across from each other. An O-ring at the bottom of the cylinder was used to provide an airtight
fit between the cylinder and the wooden box flange. The design of the sample holder allowed it to be quickly removed from the wooden box plenum and flipped such that the grain column could be reversed with respect to the airflow direction, thus allowing experimental simulation of grain inversion.

Six fiber-mesh woven pouches were used to each hold approximately 50 g of rice. The rice was taken from the same lot as that used to fill the sample holder. The six pouches were placed at equidistant locations (0, 76, 152, 229, 305, and 381 mm from the plenum) within the grain column during filling of the sample holder. The use of these pouches facilitated collection of rice samples from specific locations within the column after the completion of a drying run. At the end of each drying run, the rice samples from the pouches were used for fissured kernel enumeration and MC determination. The bulk rice sample surrounding the woven pouches was used for HRY determination and MC determination.

Drying runs

Drying runs were performed in the lab dryer to investigate the effect of grain inversion on rice fissuring and HRY at four plenum air temperatures (table 1). The plenum air RH corresponding to each temperature level was selected such that each plenum air condition had a humidity ratio of 0.012 kg water kg\(^{-1}\) dry air; this humidity ratio is typical for ambient air during the rice drying season in the U.S. mid-South.

The drying duration for each drying run was 60 min. For each of the plenum air temperatures, three grain inversion scenarios were tested: no grain inversion (0 GI), one grain inversion (1 GI), and two grain inversions (2 GI). For the drying runs in which no grain inversion was performed, the rice was dried continuously for 60 min. For drying runs with one grain inversion, the grain column orientation was reversed 30 min into the drying run, and for drying
runs with two inversions, the orientation of the column was reversed at 20 min and at 40 min to simulate two grain inverters in a column. The drying runs were replicated, and the order of drying runs for each drying air condition was randomly assigned. Thus, 24 drying runs (4 drying air conditions × 3 grain inversions × 2 replications) were performed. Immediately after drying and tempering, MC was determined on each woven pouch sample and bulk rice by drying a 15 g sample for 24 h in a convection oven, which was operated at 130°C (Jindal and Siebenmorgen, 1987). The final MCs are shown in table 2.

Prior to each drying run, rice was taken from cold storage and equilibrated to room temperature in closed plastic bags for 24 h. Approximately 3,000 g of rice was used for each drying run, of which approximately 50 g was placed in each of the six woven pouches. The six woven pouches, the remaining rice (~2,700 g), and a miniature data logger (Hobo MX1101, Onset Computer Corp., Bourne, Mass.) were placed in the cylinder so that the datalogger was located at mid-height, i.e., 190 mm from the top of the heated-air plenum. To perform grain inversion, the cylinder was raised from the wooden box, vertically flipped, and then refitted to the wooden box; the duration required to perform a grain inversion was approximately 10 s. For all drying runs, the average airflow rate through the rice was measured to be 0.7 ±0.1 m³ s⁻¹ m⁻² using a vane-type anemometer (HHF141, Omega Engineering, Norwalk, Conn.) at the exhaust end of the grain column.

After completion of a drying run, the rice in the cylinder was placed in a plastic bucket, and the temperature and RH datalogger that was used in the cylinder was placed in the rice to measure the rice temperature. Immediately thereafter, the rice was quickly divided into portions for one of two tempering approaches. Approximately half of the bulk rice sample was tempered by placing the rice in a sealed airtight plastic bag that was placed in an incubator maintained at
the average bulk-rice temperature after drying, as determined from preliminary drying runs; this tempering approach is referred to herein as heated tempering (HT). The remaining half of the bulk rice sample from each drying run was similarly placed in a sealed airtight plastic bag, but this bag was placed at ambient room temperature (22°C), referred to herein as ambient tempering (AT). Both HT and AT samples were held in their respective tempering environments for 4 h. The rice in each woven pouch was placed in its own sealed plastic bag and tempered for 4 h in the same incubator described above and maintained at the average bulk-rice temperature after drying. Each pouch sample was thus tempered using the HT method. For each drying run, a portion of rice was taken before drying and treated as a control sample on which no column drying or tempering was performed.

After drying and tempering, all samples, including the control samples, from each drying run were gently equilibrated to 12.5% ±0.5% MC by spreading the rice on screen trays and placing the trays in a controlled-environment chamber maintained at 25°C and 55% RH. Once equilibrated, all rice samples were stored at 4°C in airtight plastic bags to await enumeration of fissured kernels and HRY determination.

In commercial-scale cross-flow drying systems, the rice exiting a dryer is typically placed immediately in bins to temper. The air temperature inside the tempering bins is usually not controlled, and thus the tempering temperature depends on such factors as the drying air temperature used in the dryer, the amount of rice in the tempering bin, the duration that the rice is kept in the bin, the design of the bin, and weather conditions. Despite variations in these factors, the air temperature inside a tempering bin will typically be between the ambient air temperature outside the bin and the bulk average temperature at which the rice leaves the drying column. Therefore, the two tempering methods used in this study, AT and HT, were reasoned to
provide the minimum and maximum limits, respectively, for air conditions in a commercial tempering bin. Similarly, the number of fissured kernels and HRYs measured for the AT and HT tempering methods in the lab-scale dryer is expected to be within the range of values incurred in commercial cross-flow drying.

**Fissure detection and enumeration**

Rice samples from all pouches were tempered immediately after drying using the HT approach for 4 h and then gently equilibrated to 12.5% MC before fissure detection and enumeration began. For each pouch sample, five replicate sub-samples, each comprising 50 randomly selected rough rice kernels, were evaluated for fissures using an X-ray system (UltraFocus 60, Faxitron Bioptics, Tucson, Ariz.) at 3× magnification. Hence, a total of 250 rough rice kernels were examined per pouch sample. Alternatively, five X-ray images, with each image encompassing 50 kernels, were taken for each pouch sample, and this was done at each of the six distances from the heated-air plenum within the drying column. As such, 30 X-ray images, representing 1,500 viewed kernels, were taken per drying run. Thus, for the 24 drying runs, 720 X-ray images, representing 36,000 viewed kernels, were taken. Additionally, fissures were enumerated on the control samples from each drying run to provide data on the pre-existing number of fissured kernels in each sample. For the control samples, a total of 120 X-ray images, representing 6,000 viewed kernels, were taken. The proportion of fissured kernels in each selected sample was reported as the number of fissured kernels expressed as a percentage of the examined kernels. The fissured-kernel percentages (FKPs) for X-ray imagining replicates and drying replicates were averaged for subsequent analyses.
Milling analyses

Before milling, rice samples were taken from the refrigerated storage and equilibrated (in sealed plastic bags) to room temperature (~22°C) for at least 24 h. Approximately 150 g of rough rice was dehulled using a rice sheller (THU-35A, Satake Engineering, Tokyo, Japan) with a roller clearance of 0.48 mm to produce brown rice. The brown rice was then milled for 30 s using a laboratory mill (McGill No. 2, Rapsco, Brookshire, Tex.) equipped with a 1,500 g mass positioned on the mill lever arm 150 mm from the centerline of the mill chamber.

Intact kernels (head rice) were separated from broken kernels using a shaker table (Grainman 61-115-60, Grain Machinery Manufacturing, Miami, Fla.), and the resulting mass of head rice was expressed as a percentage of the 150 g of rough rice to produce the HRY. To determine if all samples had been milled to the same degree, the surface lipid content (SLC) of the head rice was determined by scanning approximately 50 g of head rice kernels using near-infrared reflectance (DA7200, Perten Instruments, Hägersten, Sweden), as described by Grigg and Siebenmorgen (2016). To account for variations in SLC, HRYs were adjusted to a 0.4% SLC using the following equation:

\[ \text{HRY at 0.4\% SLC} = \text{HRY at measured SLC} + 19.148 \times (0.4 – \text{measured SLC}) \]

where 19.148 is the slope of the HRY-SLC plot that was determined by milling rice from the same lot for several durations (data not reported). This method of adjusting HRY is based on the linearity of the HRY-SLC relationship described by Cooper and Siebenmorgen (2007). For samples from each drying run, HRY reduction (HRYR, percentage points) was determined by subtracting the drying sample HRY from the HRY of the corresponding control sample. Because the control samples were gently dried at 25°C, the HRY of those samples was generally considered to represent that of rice with no drying-induced fissures. The least squares means of
fissured kernel percentages and HRYR for drying runs were calculated using JMP Pro statistical software (ver. 15.1.0, SAS Institute, Cary, N.C.). Least squares means are means for treatment levels that are adjusted for means of other factors in a model.

RESULTS AND DISCUSSION

Fissured kernels

*Plenum air temperature*

The FKPs from all drying runs are shown in figure 3. Fissured kernel percentages generally increased with drying air temperature and tended to be greater near the heated-air plenum (HAP) for 0 GI; this was particularly true at greater plenum air temperatures such as 55°C and 60°C. When drying at a plenum air temperature of 55°C with 0 GI, the FKP increased from approximately 5% midway into the grain column to 15% at the HAP. Similarly, when drying at a plenum air temperature of 60°C with 0 GI, the FKP increased from approximately 11% midway into the grain column to 44% at the HAP. When drying at plenum air temperatures of 45°C or 50°C, the FKP across the grain column was fairly consistent in the ranges of 7% to 12% and 6% to 10% at plenum air temperatures of 45°C and 50°C, respectively, regardless of the distance from the HAP.

Tempering of rice at the drying air temperature immediately after drying has been shown to allow intra-kernel MC and material state gradients created during drying to subside, thus minimizing kernel fissuring (Schluterman and Siebenmorgen, 2007). Intra-kernel material state gradients are the differences in material properties within individual rice kernels due to temperature and MC gradients generated during drying (Perdon, 1999). If drying is prolonged, some kernels may experience severe intra-kernel material state gradients due to drying that result in fissuring; as such, tempering may not prevent those kernels from fissuring. For this reason,
plenum air temperatures of 55°C and 60°C, kernels closer to the HAP, particularly when there was no grain inversion (0 GI), experienced prolonged drying and severe intra-kernel material state gradients, leading to greater FKPs. However, if drying is not prolonged and is done at low plenum air temperatures such that severe intra-kernel material state gradients are avoided, tempering such as that provided by the HT approach would minimize fissure formation, as was the case when drying at plenum air temperatures of 45°C and 50°C.

**Number of grain inversions**

At low plenum air temperatures, such as 45°C and 50°C, there were no differences in FKPs due to the number of grain inversions. This is because at 45°C and 50°C, as aforementioned, severe intra-kernel material state gradients that would result in kernel fissuring had been averted. However, as the plenum air temperature was increased to 55°C or 60°C, the impact of grain inversion became apparent in that at the HAP, 1 and 2 GIs resulted in lesser FKPs than that of 0 GI, and 1 GI resulted in lesser FKPs than 2 GIs. When 1 or 2 GIs were performed, prolonged drying that would result in severe intra-kernel material state gradients at the HAP is proposed to have been averted, thus leading to lesser FKPs than with 0 GIs. On the other hand, at the exhaust of the grain column, at a plenum air temperature of 60°C, 1 and 2 GIs resulted in greater FKPs than those observed midway into the grain column, with 1 GI resulting in greater FKPs than 2 GIs. The reasons for the increase in FKPs at the exhaust of the grain column with 1 or 2 GIs are discussed later.

**Distance from the heated-air plenum**

At plenum air temperatures of 55°C and 60°C, there was an apparent increase in the FKPs for samples at the HAP (0 mm) and at the exhaust (381 mm). The trend was that when 1 or 2 GIs were performed, there was an increase in FKPs for the samples at the exhaust, particularly
at 60°C. On the other hand, when 0 GI was performed, the trend of increasing FKPs at the exhaust was not apparent; instead, an increase in FKP was observed only at the HAP. This trend is rational, as kernels located next to the HAP would have remained there for the entire 60 min of drying for the case of 0 GI; hence, the kernels incurred severe intra-kernel material state gradients due to prolonged drying. The kernels located next to the HAP when 1 GI was performed had lesser FKP than when 0 GI was performed. When 1 GI was performed, kernels at both ends of the drying column would have been next to the HAP for half of the drying duration. After inversion, the kernels that were previously next to the HAP would have been exposed to cooler and moist air, thereby drastically reducing the rate of drying. Performing 2 GIs at plenum air temperatures of 55°C and 60°C resulted in lesser FKP at the HAP compared to 0 GI but greater FKP compared to 1 GI. This is because the kernels located at 0 mm were next to the HAP for two-thirds of the drying duration with 2 GIs and only half of the drying duration with 1 GI. Likewise, on the exhaust side of the grain column (381 mm from the HAP), with 0 GIs, the kernels located at 381 mm were farthest from the HAP for the entire drying duration, hence lesser FKPs were observed. When 1 GI was performed, there were greater FKPs for the samples at the exhaust (381 mm) because those kernels were closest to the HAP for half of the drying duration. At 60°C, the trend for the kernels located 381 mm from the HAP was that 2 GIs resulted in greater FKPs than with 0 GI but lesser FKPs than with 1 GI. This is because the kernels at 381 mm were next to the HAP for half of the drying duration when using 1 GI, whereas the kernels at 381 mm were next to the HAP for only one-third of the drying duration when using 2 GIs.

In summary, at plenum air temperatures of 45°C and 50°C, grain inversion had no effect on FKPs. At such low plenum air temperatures, severe intra-kernel material state gradients were
not created during drying, and hence kernels did not fissure due to prolonged drying. On the other hand, at high plenum air temperatures such as 55°C and 60°C, grain inversion had an effect on FKPs. When 0 GIs were performed, the kernels closest to the HAP experienced prolonged drying, leading to severe intra-kernel material state gradients and resulting in kernel fissuring. When 1 or 2 GIs were performed, continual prolonged drying of the kernels next to the HAP (0 mm) was averted; as such, the intra-kernel material state gradients were not as severe as with 0 GI, resulting in lesser FKPs for 1 and 2 GIs than for 0 GI at the HAP. For plenum air temperatures greater than 50°C, 1 or 2 grain inverters in a cross-flow dryer may greatly minimize the FKP due to drying. However, to achieve uniformity in drying across a grain column, Prakash and Siebenmorgen (2018) reported that 1 grain inverter within a cross-flow dryer led to greater MC uniformity than 0 or 2 GIs.

**Head rice yield reduction**

Head rice yields of bulk samples from each drying run, listed in table 1, were determined for samples tempered using the AT and HT methods as well as for the control samples from each drying run. Head rice yield reductions were computed as the difference between the HRY of a dried sample and that of the respective control sample. These HRYRs are shown in figure 4.

**Tempering approach**

The magnitude of HRYRs for the AT samples was generally greater than that for the HT samples (fig. 4). Heated tempering allows the intra-kernel MC gradients created during drying to subside before the kernels are cooled; thus, the HT samples were expected to have minimal fissuring and subsequently minimal HRYRs. The differences between AT and HT were greater at 55°C and 60°C than at 45°C and 50°C, as shown in figure 4, which is plausible because greater plenum air temperatures would create greater intra-kernel material state gradients during
drying, and thus tempering would have a greater impact. This corroborates previous studies that showed heated tempering immediately after drying at the drying air temperature minimized HRYRs (Schluterman and Siebenmorgen, 2007; Ondier et al., 2012).

**Plenum air temperature**

As the plenum air temperatures increased, there was an increase in HRYRs for AT and HT, as shown in figure 4. The increase in HRYR due to the plenum air temperature was greater for AT than for HT. Drying at a plenum air temperature of 60°C resulted in significantly greater HRYRs than drying at plenum air temperatures of 45°C, 50°C, and 55°C for AT. For HT, drying at a plenum air temperature of 60°C with 0 GIs led to significantly greater HRYRs than drying at plenum air temperatures of 45°C, 50°C, and 55°C. Drying at plenum air temperatures of 45°C, 50°C, and 55°C led to progressively lesser HRYRs than drying at 60°C, particularly for the AT samples; this trend could be attributed to severe intra-kernel material state gradients that the kernels may have experienced during drying at 60°C for 60 min and during cooling (AT) before the material state gradients subsided. This observation corroborates the FKPs shown in figure 3. At plenum air temperatures less than 60°C, depending on the initial MC of the rice lot, most kernels may remain in a glassy state during the drying process. As a result, severe intra-kernel material state gradients could have been averted, leading to lesser HRYRs even when the samples were not tempered (AT) immediately after drying.

**Number of grain inversions**

At plenum air temperatures of 45°C, 50°C, and 55°C for both the AT and HT approaches, there were no significant differences in HRYRs due to the number of grain inversions, but there was a general stepwise trend of decreasing HRYRs with an increasing number of grain inversions at plenum air temperatures of 50°C and 55°C for both tempering approaches (fig. 4).
At a plenum air temperature of 45°C, the aforementioned trend did not exist. Instead, there was a trend of increasing HRYRs with an increasing number of grain inversions, particularly for AT samples. The reason for this different trend is not known. At a plenum air temperature of 60°C for AT samples, there were no significant differences between HRYRs for 0 and 1 GIs nor for 1 and 2 GIs. However, there was a significant difference between HRYRs for 0 and 2 GIs; 2 GIs resulted in lesser HRYR than 0 GI. On the other hand, for HT samples at 60°C, 0 GI had significantly greater HRYRs than 1 GI but was not significantly greater than 2 GIs. Generally, for both the AT and HT approaches, samples dried at plenum air temperatures of 45°C, 50°C, and 55°C showed that grain inversion had no effect on HRYR. For plenum air temperatures greater than 55°C, grain inverters in a cross-flow dryer minimized kernel fissuring and reduced HRYRs.

**CONCLUSIONS**

Experiments were conducted to quantify the impact of grain inversion during drying of rough rice in a cross-flow dryer on the fissured kernel percentage (FKP) and head rice yield reduction (HRYR). Drying at plenum air temperatures of 55°C and 60°C with no grain inversion resulted in increased fissuring of kernels next to the heated-air plenum (HAP). Grain inversion (1 and 2 GIs) reduced the FKP of samples next to the HAP at temperatures of 55°C and 60°C. At plenum air temperatures of 45°C and 50°C, the FKPs across the grain column for 0, 1, and 2 grain inversions were not different from that of the control samples. Thus, 1 or 2 grain inverters can reduce the FKP at plenum air temperatures of 55°C and 60°C, but grain inverters had no effect on the FKP at plenum air temperatures of 45°C and 50°C. However, the implications of having no grain inversion (0 GI) on MC uniformity across the grain column should be considered.
Similarly, for HRYR, 1 or 2 GIs minimized the HRYR of samples dried at plenum air temperatures greater than 55°C for both ambient tempering (AT) and heated tempering (HT). On the other hand, grain inversion had no effect on HRYR at plenum air temperatures of 55°C or less. These findings may be valuable in designing cross-flow dryers by informing decisions on the number of grain inverters needed to reduce kernel fissuring and minimize HRYR.

**ACKNOWLEDGEMENTS**

The authors acknowledge the financial support by the corporate sponsors of the University of Arkansas Rice Processing Program and the Arkansas Rice Research and Promotion Board.
FIGURES AND TABLES

Figure 1. Schematic of (a) cross-flow dryer, (b) grain inverter inside a grain column, and (c) airflow reversal in a grain column.
Figure 2. (a) Schematic of the laboratory-scale, stationary-bed grain dryer, (b) key dimensions of the cylindrical acrylic-glass sample holder, and (c) magnified view showing the assembly of various components of the cylindrical sample holder.
Figure 3. Comparison of the proportion of fissured kernels within a grain column at different distances (0, 76, 152, 229, 305, and 381 mm) from the heated-air plenum for 0, 1, and 2 grain inversions (GI) at plenum air temperatures of 45°C, 50°C, 55°C, and 60°C and tempered for 4 h at the bulk grain temperature at the end of drying using the heated tempering (HT) method. Each data point is a least squares mean of two drying run replications and ten 50-kernel X-ray images. Control samples were gently dried to 12.5% MC and received a similar X-ray examination for fissures. The details for each drying run are shown in table 1.
Figure 4. Head rice yield reduction (HRYR, percentage points) of rice samples dried in a lab-scale cross-flow dryer using 0, 1, or 2 grain inversions (GI) at plenum air temperatures of 45°C, 50°C, 55°C, or 60°C and tempered using an ambient-temperature or heated-temperature tempering approach. Each experimental data point is a least squares mean of two drying run replications. The head rice yield (HRY) of each rice sample was determined at a surface lipid content (SLC) of 0.4. Error bars indicate standard errors of the replicate least squares means.
Table 1. Initial grain and plenum air conditions for drying runs.[a]

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<tr>
<td>(4)</td>
<td>45.2</td>
</tr>
<tr>
<td>(°C)</td>
<td>(0.1)</td>
</tr>
<tr>
<td>Plenum air RH (%)</td>
<td>20</td>
</tr>
<tr>
<td>Initial rice MC (% w.b.)</td>
<td>18.3</td>
</tr>
<tr>
<td>(°C)</td>
<td>(0.1)</td>
</tr>
<tr>
<td>Initial rice temperature</td>
<td>20</td>
</tr>
<tr>
<td>(°C)</td>
<td>(1)</td>
</tr>
<tr>
<td>Drying duration (min)</td>
<td>60</td>
</tr>
<tr>
<td>Inversion treatments (3)</td>
<td>0, 1, 2</td>
</tr>
<tr>
<td>Number of replicate drying</td>
<td>2</td>
</tr>
<tr>
<td>runs</td>
<td></td>
</tr>
<tr>
<td>Total number of drying runs</td>
<td>4 × 3 × 2 = 24</td>
</tr>
</tbody>
</table>

[a] Values in parentheses are standard deviations in measured values for the various drying runs.
Table 2. Final moisture contents of rice samples from each of the 24 drying runs.

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<thead>
<tr>
<th>Target plenum air temp. (°C)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
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<th>16</th>
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<th>18</th>
<th>19</th>
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<td>12</td>
<td>12</td>
<td>12</td>
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</tr>
<tr>
<td>Number of grain inversions</td>
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<td>1</td>
<td>2</td>
<td>2</td>
<td>0</td>
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</tr>
<tr>
<td>Replicate number</td>
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<td>2</td>
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<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Actual plenum air temp. (°C)</td>
<td>45.1</td>
<td>45.2</td>
<td>45.2</td>
<td>45.0</td>
<td>45.4</td>
<td>45.2</td>
<td>50.1</td>
<td>50.0</td>
<td>50.2</td>
<td>50.1</td>
<td>50.0</td>
<td>50.1</td>
<td>54.6</td>
<td>55.3</td>
<td>55.1</td>
<td>55.2</td>
<td>55.0</td>
<td>55.0</td>
<td>60.0</td>
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<td>60.0</td>
<td>59.5</td>
<td>60.0</td>
<td>59.9</td>
</tr>
<tr>
<td>Rice temp. before drying (°C)</td>
<td>19.1</td>
<td>20.7</td>
<td>21.0</td>
<td>20.8</td>
<td>20.7</td>
<td>20.6</td>
<td>19.4</td>
<td>19.5</td>
<td>15.0</td>
<td>21.1</td>
<td>16.6</td>
<td>20.2</td>
<td>19.6</td>
<td>21.0</td>
<td>20.7</td>
<td>21.2</td>
<td>21.4</td>
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<td>23.0</td>
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<td>16.6</td>
<td>22.0</td>
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<tr>
<td>Rice MC before drying (% w.b.)</td>
<td>18.4</td>
<td>18.2</td>
<td>18.4</td>
<td>18.2</td>
<td>18.4</td>
<td>18.3</td>
<td>16.6</td>
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<td>17.1</td>
<td>16.8</td>
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<td>16.6</td>
<td>17.0</td>
<td>18.9</td>
<td>19.2</td>
<td>19.2</td>
<td>18.7</td>
<td>19.0</td>
<td>19.2</td>
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</tr>
<tr>
<td>Rice MC after drying (% w.b.)</td>
<td>14.7</td>
<td>14.5</td>
<td>15.0</td>
<td>14.9</td>
<td>15.0</td>
<td>15.1</td>
<td>12.3</td>
<td>12.3</td>
<td>12.6</td>
<td>12.5</td>
<td>12.7</td>
<td>13.0</td>
<td>12.0</td>
<td>12.4</td>
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<td>12.0</td>
<td>12.3</td>
<td>12.7</td>
<td>13.7</td>
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<td>13.7</td>
<td>13.0</td>
<td>13.8</td>
<td>13.7</td>
</tr>
<tr>
<td>Rice MC after drying (% w.b.)</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>14.7</td>
<td>14.6</td>
<td>14.8</td>
<td>12.7</td>
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<td>12.8</td>
<td>12.9</td>
<td>11.9</td>
<td>12.7</td>
<td>12.3</td>
<td>12.0</td>
<td>12.5</td>
<td>12.6</td>
<td>12.8</td>
<td>12.6</td>
<td>14.1</td>
<td>13.2</td>
<td>13.9</td>
<td>13.5</td>
<td></td>
</tr>
</tbody>
</table>

Rice MC after drying samples located at indicated distances from the heated-air plenum (% w.b.).

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>0 mm</th>
<th>76 mm</th>
<th>152 mm</th>
<th>229 mm</th>
<th>305 mm</th>
<th>381 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice MC after drying (% w.b.)</td>
<td>13.7</td>
<td>14.1</td>
<td>14.5</td>
<td>15.0</td>
<td>15.3</td>
<td>15.7</td>
</tr>
</tbody>
</table>

[a] Moisture content determined after drying and ambient tempering for 4 h.
[b] Moisture content determined after drying and heated tempering for 4 h.
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OVERALL CONCLUSIONS

Minimizing rice kernel fissuring during the drying process is an important goal of the rice industry. Various hypotheses have been proposed to explain fissure formation during drying. One such hypothesis is the glass transition hypothesis; which attributes fissure formation to intra-kernel material state gradients created during the drying process. As such, the purpose of this dissertation was to utilize X-ray imaging and glass transition principles to provide a better understanding of the fissuring kinetics, fissure characteristics, quantify the role of tempering on fissuring, and elucidate the effect of grain inversion on fissure formation and the resulting milling yields. The four main objectives addressed by this dissertation are: 1) to determine the kinetics of rough rice fissuring during the drying process and subsequent storage, and to characterize the configuration of fissures formed in rough rice kernels during drying and subsequent storage, 2) to apply X-ray imaging to validate the glass transition hypothesis in explaining rough rice fissuring due to active drying using drying air conditions selected to allow different kernel portions to be at select regions of a rice material state diagram, 3) to identify the maximum percentage points (pp) of moisture content (PPMC) reduction that can be achieved in a single drying pass for tempered rice samples versus for non-tempered (immediately cooled) rice samples without causing severe kernel fissuring, and 4) to examine the role of grain inversion on rice kernel fissuring and head rice yield reduction in relation to the glass transition hypothesis.

The instances in which fissures form and appear during the drying process are not well understood. Studies that have attempted to address this issue used an invasive method to view fissures, which consisted of removing husks to observe fissures. Thus, different sets of rough rice kernels were evaluated at each time-point for a given drying and post-drying duration. As such, there is no data in the literature for the fissuring kinetics of rough rice, the form in which rice is
typically dried and stored. This study showed that the majority of the fissured kernels had the fissure appear after active drying had ceased, typically during the tempering period. Few kernels fissured after the tempering period thus confirming that sufficient tempering after drying can greatly minimize fissuring. Generally, no additional kernel fissures were observed 12 h after drying had ceased. These findings may guide rice drying researchers and practitioners on when to enumerate fissures in rough rice kernels, at least 12 h after active drying has ceased, to account for all kernels that might fissure due to the drying process.

The glass transition hypothesis was proposed to explain fissure formation during drying. While various laboratory milling studies have collaborated the hypothesis in explaining rice head rice yield reduction, a comprehensive validation of this hypothesis from a fundamental fissuring standpoint was required. Such validation was made possible with the availability of an X-ray imaging system that allows for fissure detection in rough rice kernels during the drying process. The results validated the glass transition hypothesis and its application in minimizing kernel fissuring. It was also confirmed that drying air temperature, drying air EMC associated with rough rice, and rough rice MC will determine the position of the kernel surface and core on a rice material state diagram during drying. Controlling any of these three factors while applying the glass transition principles can significantly minimize kernel fissuring during the drying process.

Tempering is a holding process between drying passes that allows intra-kernel MC and material state gradients generated within rice kernels during drying to subside thus minimizing kernel fissuring. Various laboratory experiments have provided data that shows tempering to reduce kernel fissuring and minimize HRYR. However, the benefits of tempering on minimizing kernel fissuring have not been quantified for various drying conditions. To maximize dryer efficiency, it may be useful to know how much MC reduction can be achieved in a single drying
pass without significantly fissuring rice kernels for tempered samples and non-tempered samples. Similarly, quantifying the benefits of tempering on minimizing kernel fissuring for a range of drying conditions will be useful to rice drying practitioners. Results showed that an extra 1-2 pp of MC reduction could be achieved in a single drying pass without significant kernel fissuring if the kernels are tempered at the drying air temperature after drying as compared to samples that are not tempered. Similarly, tempering was shown to reduce the FKP by up to 50% of that when kernels were not tempered after drying. These findings confirm and quantify the importance of post-drying tempering during the rice drying process, thus collaborating the glass transition hypothesis and previous studies that have recommended tempering after each drying pass as a means to reducing kernel fissuring and minimizing head rice yield reductions.

In cross-flow dryers, rice kernels at different locations across the column thickness dry at different rates due to drastically different drying air conditions across the column, which creates non-uniformity in drying. Such non-uniformity within cross-flow dryers can cause under- or over-drying of rice and fissuring of kernels, which reduces HRY. To improve uniformity in drying, industrial-scale cross-flow dryers are often equipped with grain inverters. While several researchers have investigated the use of cross-flow grain dryers, the role of grain inversions on kernel fissuring and HRYR has not been investigated. This study examined the role of grain inversions on rice kernel fissuring and HRYR in relation to the glass transition hypothesis. Results showed that grain inversion minimized kernel fissuring at plenum air temperatures ≥55°C but had no effect on kernel fissuring at plenum air temperatures <55°C. Similarly, grain inversion decreased HRYR for samples dried at plenum air temperatures >55°C. This study further showed that one or two grain inverters in a cross-flow dryer can reduce kernel fissuring and minimize HRYR. These findings may be valuable for designing cross-flow dryers by
informing decisions on the number of grain inverters needed to minimize kernel fissuring and HRYR, and the plenum air temperatures at which grain inversion is beneficial in minimizing the reduction in milling yields.