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Experimental Simulation of a Cross-flow Rice Dryer

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Experimental Simulation of a Cross-flow Rice Dryer

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by

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ABSTRACT

After harvest, rough rice is dried, then dehulled and typically milled before consumption. A broad objective of the "rice drying process", which comprises drying and tempering, is to maximize the yield of "whole, intact milled kernels", quantified by the "head rice yield" (HRY). Since rough rice is commonly dried using cross-flow (CF) dryers in the United States of America, the aim of this research was to assess the effect of drying and tempering treatments on milling yields when rice was dried in an experimentally-simulated CF drying column. First, because airflow rate was found to be the least-studied "drying variable", its effect on drying air conditions and rice moisture content profiles was assessed. Additionally, the impact of airflow rate on the material state behavior of rice kernels was considered as a means to explain head rice yield reductions (HRYRs). Second, the effect of tempering approach following CF drying on milling yields was investigated. For the same rice and drying conditions, tempering approach significantly affected HRYs, especially HRYs of samples that were located near the heated-air plenum during CF drying. Third, drying treatments were selected based on the glass transition temperature of rice kernels and applied in the drying column. When kernels did not undergo material state transitions during drying, there was negligible HRYR, regardless if samples had been tempered or not. But, when kernels underwent material state transitions during drying, significant HRYRs occurred, and HRYRs of tempered samples were significantly less than those of non-tempered samples.

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DEDICATION

To my parents, for everything that they have done for me.

TABLE OF CONTENTS

LIST OF PAPERS

Mukhopadhyay, S.; Siebenmorgen, T. J. Effect of Airflow Rate on Drying Air and Moisture Content Profiles inside a Cross-flow Drying Column. D*rying Technology* **2017**. Accepted manuscript. (Chapter 1)

Mukhopadhyay, S.; Siebenmorgen, T. J.; Mauromoustakos, A. Effect of Tempering Approach following Cross-flow Drying on Rice Milling Yields. To be submitted. (Chapter 2)

Mukhopadhyay, S.; Siebenmorgen, T. J. Glass Transition Effects on Milling Yields in a Cross-flow Drying Column. *Drying Technology* **2017**, 107: 253-261. (Chapter 3)

I. INTRODUCTION

Rice (*Oryza sativa L.*) is the staple food of about two-thirds of the world's population.[1] In terms of human consumption, rice is the single most important food crop in the world, providing 21% of the caloric needs of the world and 76% of that of South-East Asia.[2] The United States of America (USA) produced an average of 1.4% (9.4 mmt per year) of the global average annual rough rice production of 727.3 mmt over the 2010 - 2014 period.[3] Despite the low percentage contribution of the United States (US) to the world production in recent years, US production far exceeds its domestic demand for rice. Hence, US has consistently been the fifth largest exporter of rice, after Thailand, India, Vietnam, and Pakistan, exporting an average of 3.9 mmt per year (on a milled rice basis) over the 2010 - 2017 period.[3]

Historically, four regions produce most of the US rice crop: 1) the Arkansas Grand Prairie, 2) the Mississippi Delta, (parts of Arkansas, Mississippi, Missouri, and Louisiana), 3) the Gulf Coast (Texas and Southwest Louisiana), and 4) the Sacramento Valley of California.[4] Typically, Arkansas is the leading rice producing state in the USA, often producing nearly half of the total production; in 2016, Arkansas contributed 47.4% (5.4 mmt) of the total US rough rice production of 11.4 mmt.[4]

Rough rice is typically harvested at 14% to 22% moisture content (MC) (wet basis) in the Mid-South USA. Soon after harvest, rice needs to be dried ~ 12.5% MC (wet basis) to minimize respiration rates and mold growth,[5] as well as to inhibit fungi and insect growth.[6] Dried rough rice is then dehulled and typically milled before consumption.

Milled rice comprises "whole, intact" kernels called head rice, which are defined as milled kernels that are at least three-fourths of the original kernel length,[7] and broken kernels.

“Rice milling yield” refers to either or both the milled rice yield (MRY) and the head rice yield (HRY), defined as the mass of milled rice and head rice, respectively, expressed as a percentage of the original, dried rough rice mass.[7] Because of the economic importance of head rice relative to broken kernels, the broad objective in rice post-harvest processing and management operations, which include drying, tempering, storage and milling, is to maximize HRY.

Commercial “drying processes” for rough rice typically comprise multiple drying passes, with periods of “tempering” between passes. In the USA, rough rice is commonly dried in cross-flow column dryers using elevated air temperatures ranging from 40°C to 70°C[8-10] to achieve high throughput rates. Rice is usually passed several times through these dryers, wherein each pass removes a certain amount of moisture from the rice. Hence, “drying variables” for a given rice cultivar comprise the initial MC of the rice, desired final MC of the rice, drying air temperature and relative humidity, airflow rate through the rice columns, and the quantity of rice to be dried in a given duration (dryer throughput).

Additionally, rice is tempered between drying passes to allow intra-kernel material state gradients, which are typically created during heated-air drying, to subside.[11,12] Because intra-kernel material state gradients are allowed to subside, fissuring and consequent head rice yield reductions (HRYRs) are minimized.[12,13] Tempering also decreases the total drying duration[14,15] by improving the drying rate in subsequent passes,[16] thereby increasing overall energy efficiency.[17,18]

Since, rice is commonly dried in cross-flow column dryers is the USA, the purpose of this research was to quantify and assess the effect of various drying variables and tempering approaches on resultant milling yields in an experimentally-simulated cross-flow drying column.

This dissertation is presented in the "published/submitted papers" format, wherein each chapter is a manuscript that has either been published or is under review in a peer-reviewed journal. The specific objectives of this dissertation are as follows:

1) *Chapter 1…*(i) Measure the drying air and rice MC profiles in an experimentally-simulated cross-flow drying column when different airflow rates are used, (ii) investigate the effect of airflow rate on these profiles when rice at different initial MCs is used, and (iii) map the material state gradients created within rice kernels under a range of rice and drying air conditions.

2) *Chapter 2…*(i) Elucidate the effect of tempering approaches on milling yields of rice that had been immediately prior-dried in an experimentally-simulated cross-flow drying column, (ii) investigate the effect of rice initial MC and drying duration on these milling yields, and (iii) for each tempering approach, estimate the minimum tempering duration required to minimize HRYR. The goal of this study was to understand the effect of post-drying tempering approaches on milling yields and the extent of fissure occurrence when rice from different dryer cross-sections was tempered using different methods.

3) *Chapter 3…*(i) Quantify the effects of drying/tempering treatments on milling yields of rice located at different cross-sections of a drying column during a drying run, and then tempered or not tempered following that drying run, and (ii) study the effects of intra-kernel material state gradients on milling yields within the drying column. The goal of this study was to assess if intra-kernel material state gradients associated with the glass transition hypothesis could be used to explain the occurrence of fissures and resultant HRYRs in a cross-flow drying scenario.

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II. CHAPTER 1

Effect of Airflow Rate on Drying Air and Moisture Content Profiles inside a Cross-flow Drying Column

ABSTRACT

Rice at 20.5% and 16.3% initial moisture contents (IMCs) was dried using 57°C/13% RH air at airflow rates (Qs) of 0.36, 0.46, and 0.56 $(m^3/s)/m^2$ for 30, 60, and 90 min in an experimentally-simulated cross-flow drying column. Q significantly affected the drying air and rice moisture content profiles within the drying column; for a particular drying duration, the range of MCs within the column decreased as Q increased. Q also impacted the extents of intra-kernel material state gradients created and thus, had potential impacts on kernel fissuring and consequent head rice yield reduction. Additionally, the impact of Q on the above-mentioned profiles was dependent on the rice IMC.

INTRODUCTION

Rice is typically harvested at 14 to 22% moisture content (MC) in the Mid-South rice-growing region in the United States of America (USA) and must be dried to approximately 12.5% MC soon after harvest for safe storage. Unless otherwise specified, all MCs are reported on a wet basis (wb). In the USA, cross-flow column dryers are the most popular rice dryers used in commercial, as well as in on-farm, drying systems. Cross-flow dryers are so-called owing to the "cross-wise" direction of movement of rough rice relative to that of the heated air; rice flows vertically downwards between two perforated metal screens comprising the grain columns (Fig. 1), while heated air flows through the columns in a direction perpendicular (or "cross") to that of the rice movement. Typically, ambient air is first forced into the dryer by an axial or centrifugal fan, then heated by a burner using direct combustion of propane or natural gas, before entering the heated-air plenum (HAP) of the dryer. The height of the drying section in an on-farm cross-flow dryer is typically 4 m, whereas in commercial systems, this height may be as much as 30 m. Unloading feed-roll augers, located at the bottom of the dryer columns, combine the columns and meter the rice out of the dryer.

For a given cultivar, the initial MC (IMC) of the rice, desired final MC of the rice, type of dryer, quantity of rice to be dried in a given duration, ambient air conditions, drying air temperature and relative humidity, and airflow rate through the rice columns are all variables that impact the drying process. Airflow rate (Q) has been the least studied variable of these that can be controlled by the dryer operator. Most "thin-layer" rice drying studies have not studied the effect of Q as a process variable; some have reported the value(s) of Q used[1-3] while others have not mentioned Q at all.[4-9] This seems intuitive because a "thin-layer" is defined as a material exposed fully to an airstream during drying[10] and thus, from its very definition, is of sufficiently small product thickness such that drying air characteristics everywhere in the layer are identical. However, rice is not dried in "thin-layers" in commercial systems, but as "deep-beds" with typical thicknesses of the drying column in cross-flow dryers varying between 0.25 m and 0.45 m. Conceptually, "deep-bed drying" differs from thin-layer drying; deep-bed drying refers to heterogeneous drying of grain in a "deep/thick layer" where drying is faster at the drying air inlet than at the exhaust. Thus, it follows that the air, as well as grain, properties change considerably as a function of distance from the HAP.

Over the last seven decades, deep-bed modeling and simulation studies have been conducted for rice[11-18] but none of these elaborated on the effect of Q on drying characteristics, including the quality of the dried product. Only a few deep-bed studies included the effect of

Q.[19-21] It was reported that Q significantly affected the drying rate of rice[21] in a deep-bed, and the MC profiles within a deep-bed of rice.[19] Additionally, very few studies were conducted on actual cross-flow dryers, and none were found that elaborated on Q as a process variable.[22-26] Other researchers studied specific dryers and(or) dryer configurations.[5,27-31]

While a few deep-bed studies included the effect of Q in cfm/bu (commonly used in the USA, especially in bin-drying; cfm/bu refers to the volume of air flowing through a unit volume of grain), it is difficult to apply this knowledge in terms of the actual superficial velocity of the air flowing through a bed of grain since dryer dimensions were not provided in these studies. Superficial velocity, also known as "apparent velocity", refers to the product of the true interstitial velocity of air and the porosity/void fraction of the packed bed of particles.[32] Additionally, rice cross-flow dryers are often operated at elevated temperatures (40 - 70°C) to achieve high throughput rates. The drying conditions from deep-bed studies or other dryer configurations are different from those used in a cross-flow dryer, for example, natural air in-bin drying uses ambient air (3 to 8°C) to dry rice over a period of weeks, even months[33] or slightly heated air (25 to 38°C),[34] mixed flow dryers use heated air at (43 to 78°C),[35] and fluidized-bed dryers use drying air temperatures as high as 140 to 150°C.[36] As a result, the insights gained from such studies cannot be directly applied to cross-flow dryers.

Owing to the typical elevated drying air temperatures used in cross-flow dryers and the thickness of the drying column, there is considerable variation in the temperature/relative humidity (T/RH) profile of the drying air as it moves through the "deep-bed" drying column; the air follows a path of adiabatic saturation per psychrometric relations, thus, it has maximum drying capacity at the HAP, but as it passes through the rice column, its drying capacity progressively decreases as moisture is evaporated from the rice. Hence, a wide range of rice MCs exists throughout a drying column; typically, rice near the HAP is inadvertently over-dried while the rice near the exhaust is under-dried.[24,37] This "non-uniformity" of drying is a major disadvantage of cross-flow dryers, especially for rice drying, since such severe drying can result in kernel fissuring, which in turn, can lead to severe head rice yield (HRY) reductions. In fact, HRYs of samples obtained from the vicinity of the HAP were significantly less than those of samples located further from the HAP of a commercial cross-flow dryer operating at drying air temperatures ranging from 40 to 65°C in multiple passes that lasted approximately 20 to 40 min each.[24] Since HRY, the mass of head rice (milled kernels that are at least three-fourths of the original kernel length) expressed as a percentage of the original, dried rough rice mass,[38] serves as a direct determinant of the economic value of rice, the broad objective in any rice drying operation is to minimize fissuring and consequently, maximize HRY.

Fissuring, and consequent breakage in rice kernels during the drying process has been hypothesized to occur primarily due to differences in properties of the amorphous regions of starch above and below glass transition temperature (T_g).[4] Intra-kernel material state gradients were shown to influence fissuring and consequent HRY reductions in several thin-layer studies[4,7] and in one deep-bed study, which experimentally-simulated a cross-flow drying column.[39] Owing to the MC of the rice kernels and the operating conditions of cross-flow dryers, kernels may undergo intra-kernel material state transitions from the glassy to the rubbery state and vice versa during the drying process, which, could potentially "position" different volumes of the kernel periphery on either side of the T_g line, i.e., in the glassy/rubbery regions. Depending upon the relative volumes of glassy/rubbery regions created within a kernel, the kernel may fissure owing to the vastly different mechanical properties of these two regions. Although the effect of drying air T/RH and that of drying duration on the drying trajectory of the bulk rice and its relative position on the "glassy/rubbery state diagram"[40] with respect to the T_g line were studied,[39] the researchers conducted all experiments at one value of Q and thus, did not study the effect of Q in creating different extents of intra-kernel material state gradients in a cross-flow drying scenario. It is hypothesized that varying Q, while keeping all other drying air and rice conditions the same, will have implications on the drying trajectory of the bulk rice and its relative position on the state diagram with respect to the T_g line and that this will yield more insight into the extent of kernel fissuring as applied to a "deep-bed" cross-flow drying scenario.

Communication with experts in the industry and a preliminary field test revealed that the effect of varying Q in on-farm and commercial rice cross-flow dryers is not well-known. Additionally, the authors are not aware of any existing study on cross-flow dryers or experimental simulations of such dryers that measure the drying air profiles, as well as the rice MC profiles under typical operating conditions of cross-flow dryers when different Qs were used. Thus, it was deemed necessary to conduct a study with the following objectives: 1) measure the drying air profiles and rice MC profiles in an experimentally-simulated cross-flow drying column for different Qs, 2) investigate the effect of Q on the above-mentioned profiles when rice at different IMCs is used, and 3) map the material state gradients created within rice kernels under a range of rice and drying air conditions. An over-arching goal of the experimentation conducted in this study was to generate data to validate a cross-flow drying model.[37]

MATERIALS AND METHODS

Overview of the experiment. Information about levels of Q currently used in the rice drying industry was collected from industry experts and a preliminary field test. Then, an experiment was designed to study the effect of Q on drying air and rice MC profiles in a specially-designed apparatus that allowed measurement of drying air conditions, as well as MC of rice, throughout a drying column. Rough rice at two IMCs (20.5% and 16.3%) was dried using 57°C/13% RH air at three Qs (0.36, 0.46, or 0.56 $(m^3/s)/m^2$) for three drying durations (30, 60, or 90 min), and each drying treatment was followed by one of three post-drying approaches. Each drying/post-drying approach was replicated twice, thus yielding 108 drying runs.

Preliminary experiment. The feedback received from industry experts who were requested to provide data on the levels of Q currently used in the rice drying industry suggested that in most cases, the levels of Q used in the industry are not well-known. In other instances, values were reported in cfm/bu, but mostly without accompanying dryer dimensions. Thus, it was deemed necessary to conduct a preliminary field test to ascertain the range of Qs actually used in rice cross-flow dryers.

Superficial air velocity was measured for an on-farm, cross-flow rice dryer (Portable grain 1226, GSI Group, LLC, Assumption, IL, USA) located in Pocahontas, AR, using a hand-held, rotating vane anemometer (HHF141, Omega Engineering Inc., Norwalk, CT, USA; accuracy: ±1.0% of reading ±1-digit), on the exhaust side of both of the 38-cm thick drying columns, at three equal distances along the length of the dryer. Five readings were taken at each location; the average superficial air velocity through the bed of rice was 0.46 m/s, which equates to an airflow rate (Q) of 0.46 $(m^3/s)/m^2$ of rice. Thus, in order to study the effect of Q on drying air and rice MC profiles, this value was taken as the "baseline", while two additional levels, one 21.7% greater (0.56 $(m^3/s)/m^2$) and one 21.7% less than this baseline (0.36 $(m^3/s)/m^2$) were selected for testing, thus, covering a wide range of Qs that may be used in cross-flow drying scenarios and hence, enabling the study of effect of Q on drying air profiles, as well as the rice MC profiles under typical operating conditions of cross-flow dryers.

Sample procurement and preparation. A 600-kg bulk lot of rough rice (long-grain cultivar Roy J) was combine-harvested at the University of Arkansas Rice Research & Extension Center, Stuttgart, AR, USA in September, 2015 at 23.2% MC. The lot was cleaned using a dockage tester (XT4, Carter-Day, Minneapolis, MN, USA) to remove foreign material and unfilled kernels. The bulk lot was divided into two 300-kg sub-lots, which were gently conditioned to approximately 21% and 16% MC, respectively, using air at 26°C/56% RH, and stored in sealed containers at 4°C for 4 months. Immediately prior to drying treatments, the rice MC was determined to be 20.5% and 16.3%, respectively, by drying duplicate, 15-g sub-samples in a convection oven (1370FM, Sheldon Manufacturing Inc., Cornelius, OR, USA) maintained at 130°C for 24 h.[41]

Experimental system. Drying runs were accomplished inside a 0.91-m^3, controlled-environment chamber (Platinous Sterling Series, ESPEC North America, Hudsonville, MI, USA) that was capable of producing drying air at 57°C/13% RH, with a corresponding rough rice equilibrium MC of 6.4% (Modified Chung-Post equation,[42]). This air condition is typical for use in cross-flow dryers in the Mid-South region of the USA. During operation, a centrifugal fan (4C108, Dayton Electric Manufacturing Co., Niles, IL, USA), coupled to a 0.56-kW electric motor (3N443BA, Dayton Electric Manufacturing Co., Niles, IL, USA), suctioned air at the desired T/RH from the chamber through a port located in the front door of the chamber, and then forced the air through a side-wall port in the chamber wall to a drying assembly (Fig. 2). A variable-frequency drive (AF-300 Mini, GE Fuji Drives USA Inc., Salem, VA, USA) was connected to the fan motor to achieve the desired Q. A preliminary fan calibration experiment (described below) was conducted to ensure that the desired Q was maintained during drying.

The drying assembly (Fig. 2) comprised a wooden box that served as a HAP, an acrylic glass drying column with a metallic screen base, and a set of ten, fiber-mesh cylindrical baskets (3.8-cm deep, 12.7-cm diameter). The fiber-mesh baskets were used as “sample holders” for the rough rice and enabled the drying column to be divided into discrete layers, thus permitting sampling at various distances from the HAP. Each basket had a fiber-mesh flap on top that could be fastened using metal pins, and a fiber-mesh handle to facilitate dismantling after the completion of a drying run.

Drying procedure. Approximately 2.7 kg of rough rice was removed from cold storage, placed in a sealed bag and equilibrated to room temperature (22°C) for 24 h prior to each drying run. Each of the ten baskets was filled with 270 g of rough rice. A T/RH sensor/logger (UX100-011, Onset Corporation, Bourne, MA, USA; accuracy: ±0.21°C and 2.5% RH) was placed inside each basket to measure air conditions every 60 s during drying. Stacking the ten baskets in the acrylic glass cylinder resulted in a 38-cm deep rice column. Additionally, four T/RH sensors, as shown in Fig. 2, were utilized; two were placed inside the HAP and two at the top of the rice column to record air conditions at the column inlet and exhaust, respectively. When the controlled-environment chamber stabilized at the T/RH setting for a drying run, the chamber door was opened for < 1 minute to position the rice column on the HAP. After the desired drying duration, the drying column was dismantled.

Post-drying moisture content measurement approaches. In commercial and on-farm cross-flow dryers, rice flows downward through the drying columns and feed-roll augers meter the dried rice out of the columns. Thus, the rice from a column cross-section is mixed as it exits the dryer (Fig. 1). In order to simulate this experimentally, after the drying column was dismantled following a drying run, the rice from all ten baskets was mixed together. A 40-g sample was taken from the mixed mass, allowed to equilibrate in a sealed plastic bag at 22°C for 48 h, and MC measured following the above oven-drying procedure to indicate the final average MC of the column.

Additionally, it was desired to quantify the MC of rice in each basket for a given drying treatment. To do this, a separate drying run was conducted at the same rice and drying air conditions but following that drying run, the rice from each basket was preserved as separate samples; then, a 40-g sample was taken from each basket for MC analysis to indicate the final MC as a function of distance from the HAP. For all drying/post drying treatments, the T/RH sensors were retrieved after each drying run and the data downloaded.

Fan calibration. To calibrate the variable-frequency drive, so as to determine the frequency setting corresponding to the required Qs of 0.36, 0.46, and 0.56 ($(m^3/s)/m^2$), the drying column was assembled as described above and the vane-anemometer was held above the column to measure the superficial air velocity. As the variable-frequency drive was progressively increased from 0 to 60 Hz in 5-Hz intervals, the corresponding anemometer reading was recorded. This calibration exercise was repeated with the anemometer positioned at the center of the column and as well at its periphery, to account for different air patterns across the diameter of the column. This process was repeated ten times. Q was plotted versus fan-frequency. Exponential functions were used to describe the relationships between fan-frequency and Q; from the resulting curves, the frequency settings required to obtain the desired values of Q were determined; these frequency settings were used for subsequent drying runs.

RESULTS AND DISCUSSION

General layout. Since T/RH sensors were placed inside the rice baskets before the start of every drying run, regardless of the three post-drying approaches followed, drying air profiles reported below comprise data points from all 108 drying runs. It is worth mentioning that in this article, only two out of three post-drying approaches have been described, as seen above. Additionally, figures showing drying air profiles for the 90-min drying duration include data from the 30- and 60-min drying runs. Hence, these drying air profiles comprise data points that are the mean of 18 (data from 3 drying durations (30, 60, and 90 min) X 3 post-drying approaches X 2 replications), 12 (data from 2 drying durations (60 and 90 min) X 3 post-drying approaches X 2 replications), and 6 (data from 1 drying duration (90 min) X 3 post-drying approaches X 2 replications) drying runs for the 30-, 60-, and 90-min drying durations, respectively. However, MC could be measured only after the completion of the 30-, 60-, or 90-min duration, thus, these data points are the mean of two experimental treatment replications.

Drying air profiles. Fig. 3 shows the T/RH profile of the drying air at different distances from the HAP as a function of drying duration when rough rice at 20.5% IMC was dried for 90 min using 57°C/13% RH air. The T/RH profile shown in this figure is representative of that within a drying column of an actual cross-flow rice dryer for the drying duration tested, since Q was maintained at the typical level of 0.46 $(m^3/s)/m^2$.

From Fig. 3, it is evident that this is a “deep-bed”/“thick-layer” scenario; both T and RH of the drying air changed considerably as the air passed through the drying column, which is characteristic of deep-bed drying. Additionally, although the T/RH conditions at the inlet remained fairly constant throughout the 90-min drying duration (55 ± 1°C/13 ± 1% RH), the

T/RH conditions of the exhaust varied considerably as drying progressed (38 ± 8.3°C/49 ± 25% RH), as apparent from the relatively large standard deviations in the T/RH values and the shape of the exhaust T/RH curve (Fig. 3). Likewise, the T/RH of the drying air at different locations inside the drying column changed progressively during the drying duration. These results showed that heat and mass transfer between the drying air and the rice is dependent upon drying duration.

The temperature plot in Fig. 3 shows the temperature of the drying air at 1.8 cm from the HAP; this temperature rapidly increased within 5 min from the start of the drying run and after the initial 5 min, the sensor reading remained steady/asymptotic at approximately 55°C throughout the 90-min duration, indicating that the drying air passing through the first basket of rice was at 55°C for almost the entire 90-min duration. Sensors placed further into the drying column recorded progressively lesser temperatures owing to evaporative cooling of the drying air; expectedly, the sensor placed at 36 cm from the HAP recorded the lowest drying air temperature of 46°C, showing that the temperature of the drying air decreased by 9°C as it traversed the 38-cm deep rice column. Interestingly, sensors placed further into the drying column also took progressively longer to reach their respective asymptotic temperatures; the 36-cm sensor required the longest duration (68 min) to reach its asymptotic temperature of 46°C.

Expectedly, the trends shown in the RH-plot (Fig. 3) are opposite to those of the corresponding temperature plot, with progressively increasing RH values with increasing distance into the drying bed. These trends indicated that the drying air became more and more moisture laden as it was moving through the bed of rice. Thus, as mentioned earlier, the air followed a path of adiabatic saturation per psychrometric relations, thus, the air had maximum drying capacity at the HAP, but as it passed through the rice column, its drying capacity progressively decreased as moisture was evaporated from the rice, as reflected in the air's decreasing temperature values and correspondingly increasing RH values.

Additionally, when drying commenced, the sensors near the HAP (sensors placed at 1.8, 5.6, and 9.4 cm from the HAP) showed high RH values that decreased progressively with increasing drying duration, indicating that the rice near the HAP dried considerably in the first few minutes from the start of drying. As the rice dried, i.e., its MC decreased, there were progressively lesser amounts of "free" water available to be evaporated, hence, the RH of the drying air progressively decreased. This finding corroborates previous research that as MC decreases, the strength of the water-solid bonds generally increases.[43] Interestingly, the sensors further into the drying bed (those placed at 17.0 cm, 24.6 cm, and 36.0 cm from the HAP) showed that the RH of the drying air first increased, then remained steady for a certain duration and finally, decreased. These results indicated that at first, the air picked up moisture from the rice (drying air RH increased), reached saturation for a certain duration during which no drying occurred (RH values ~ 100%), and then started drying the rice further (drying air RH decreased again). Thus, these RH trends clearly show the movement of the drying front through the 38-cm deep bed of rice at the indicated Q of 0.46 $(m^3/s)/m^2$.

It is interesting to note that the sensor placed at 36.0 cm from the HAP recorded RH values ~ 100% from 4 to 22 min of drying, indicating that no drying occurred in this part of the deep-bed throughout this duration. This trend can be seen from the 24.6 cm-sensor readings as well, only that the duration for which the air was saturated was shorter. These trends reinforce the general idea that very little drying actually occurs in the rice located near the exhaust, particularly in typical industrial cross-flow drying situations wherein the column thickness is ~ 38 cm and each drying pass is ~ 30 min long. Fig. 3 also shows that the sensor placed at the exhaust recorded a greater drying air temperature and a correspondingly lower RH than the sensor embedded in the rice 36 cm from the HAP. This trend occurred in all the drying runs in this study; a probable explanation being that the sensor embedded in the rice had a lower temperature and a correspondingly greater RH due to evaporative cooling.

Fig. 4 shows the T/RH profile of the drying air at different distances from the HAP as a function of drying duration when rough rice at 20.5% IMC was dried for 90 min using 57°C/13% RH air at all the three airflow rates used; thus, Fig. 3 is the middle set of graphs of Fig. 4. Although the overall T/RH trends remained the same, the effect of Q is apparent from Fig. 4. The temperature profiles, and in particular, the RH profiles, offer interesting insights into the drying process.

Firstly, over the 90-min duration, although the T/RH conditions at the inlet remained fairly constant at all levels of Q, the mean exhaust temperature increased while the mean exhaust RH decreased with increasing Q. For example, the mean exhaust T/RH conditions were 35 ± 7°C/52 ± 19% RH, 38 ± 8.3°C/49 ± 25% RH, and 41 ± 9°C /43 ± 26% RH for 0.36, 0.46, and 0.56 $(m^3/s)/m^2$, respectively. This general trend is also evident from the T/RH condition of the exhaust towards the end of the 90-min drying duration; with increasing Q, the asymptotic temperatures increased while the asymptotic RHs decreased. Additionally, as Q increased, the exhaust T/RH curves became “more steep” and approached their asymptotic values faster during the drying duration, reflecting that greater heat and mass transfer occurred with increasing Q.

Secondly, as Q increased, the corresponding sensors located at different distances from the HAP acquired their asymptotic T/RH values faster, also indicating greater heat and mass transfer. For example, at the least Q used (0.36 $(m^3/s)/m^2$), the temperature curves were “spread” farther apart, and the "family of curves" did not converge to a narrow band at the 90-min duration. But as Q increased progressively, the "spread" of the temperature curves decreased and the family of curves converged into a narrower band. Similar trends were noted with the RH curves as well; this was because with increasing Qs, the "contact time" between the drying air and the rice progressively decreased.

Thirdly, since the "contact time" between the air and the rice decreased with increasing Q, the sensors farther into the column recorded RHs ~ 100% for shorter durations; for example, the sensor at 36 cm from the HAP starting recording RHs < 100% after 37, 26, and 20 min of drying when Qs at 0.36, 0.46, and 0.56 $(m^3/s)/m^2$, respectively, were used. This implied that the drying front moved more quickly and farther into the drying column when greater Qs were used. Lastly, Fig. 4 also shows that most of the drying occurred in the first 30 min of drying when a typical Q of 0.46 $(m^3/s)/m^2$ was used, thus substantiating the practical operating duration of 20 - 40 min in commercial cross-flow rice dryers.[24]

Fig. 5 shows the same T/RH profiles as shown in Fig. 4, except that the IMC of the rice was 16.3%. All the general trends mentioned above are also evident with the lesser-IMC rice; however, the impact of IMC can be seen when Figs. 4 and 5 are compared. The most notable difference was that for all three levels of Q, the sensors further into the HAP recorded RHs ~ 100% for shorter durations for the 16.3%-IMC rice than those for the 20.5%-IMC rice. Additionally, these durations decreased further with increasing Qs for the 16.3%-IMC rice. This phenomenon can be explained in terms of the total energy required to dry rice from a given IMC to a desired final MC.[44] According to this study,[44] the total heat of desorption of rice (Q_t) is a function of rice MC and kernel temperature; at a given kernel temperature, Q_t decreases exponentially as MC increases. In other words, the greater the IMC, the lesser the Q_t required to dry the rice. In fact, there is a sharp increase in Q_t as rice IMC < 15%, indicating that the water is increasingly bound to the rice matrix as MC decreases.[44] Thus, the energy required to remove a unit mass of water from the rice was greater when the rice was at 16.3% IMC as compared to when it was at 20.5% IMC.

Fig. 6 shows the effect of Q on the T/RH of the drying air within the drying column at 30-, 60-, and 90-min intervals when 20.5%-IMC rice was dried. Expectedly, drying air temperature increased, while corresponding RHs decreased with increasing Q; this was true across all durations. More importantly, these drying air profiles, particularly the RH profiles, revealed an interesting trend when different levels of Q were used. After 30 min of drying, the RH-curve for the least Q of 0.36 $(m^3/s)/m^2$ showed that the drying air had rapidly picked up moisture from the rice and had actually reached saturation (RH ~ 100%) near the exhaust of the drying bed, indicating that the drying capacity of the air was fully utilized in drying the rice. When Q was increased to 0.46 $(m^3/s)/m^2$, the RHs attained near the exhaust were much less (45 to 50%), indicating that the air exited the bed of rice without having utilized its full drying capacity. At an even greater Q of 0.56 $(m^3/s)/m^2$, RHs near the exhaust decreased further to 30 to 35%, thus, even less of its drying capacity had been used to dry the rice. Expectedly, as the drying duration increased to 60 min and then to 90 min, the RHs near the exhaust decreased progressively with increasing Q, indicating that even lesser extents of the drying capacity of the air was utilized in the drying process. Hence, from an "energy-efficiency" standpoint, drying 20.5%-IMC rice for 30 min using the least Q of 0.36 $(m^3/s)/m^2$ was ideal for this 38-cm deep bed of rice because all the energy used to heat the air and blow it across the drying column had been utilized to dry the rice.

The overall trends described above (Fig. 6) were also observed when rice at 16.3% IMC was dried (Fig. 7), the only exception being that the RHs for the 16.3%-IMC rice were less than those for 20.5%-IMC rice for corresponding levels of Q and drying duration. This was expected, since the energy required to remove a unit mass of water was greater for 16.3%-IMC rice compared to the 20.5%-IMC rice to begin with.[44] Thus, from an energy efficiency standpoint, it may be better to use lesser levels of Q as rice IMC decreases, such that the drying capacity of the air is fully utilized.

Rice moisture content profiles. The bulk-column MCs after drying 20.5%- and 16.3%-IMC rice for 30, 60, and 90 min using 0.36, 0.46, and 0.56 $(m^3/s)/m^2$, respectively, are listed in Table 1. As expected from the drying air profiles shown earlier, for each drying duration, as Q increased, the bulk-column MCs decreased. In other words, as Q increased, the percentage point moisture content reduction (PPMR), defined as the difference between the initial MC and the final MC, increased. Additionally, for a particular level of Q, final bulk-column MCs decreased (or PPMR increased) with increasing drying duration. These trends were consistent across both IMCs.

Table 1 also shows that for the corresponding drying duration and the level of Q, the PPMR decreased as IMC of the rice decreased. For example, when 20.5%-IMC rice was dried for 30 min using air at 0.36 $(m^3/s)/m^2$, the bulk-column MC decreased by 2.6 percentage points (PPs). However, when 16.3%-IMC was dried using the same conditions, the bulk-column MC decreased by only 0.4 PP. This trend was consistent throughout all drying conditions; PPMRs were less for the 16.3%-IMC rice as compared to those of the 20.5%-IMC rice. As explained above, this was because as IMC decreased, the amount of energy required to remove a unit mass of water from the rice increased.[44]

Fig. 8 shows that, like the bulk-column MCs, MC of rice at a given distance from the HAP decreased with increasing Q; this occurred across all three drying durations tested. Moreover, the "non-uniformity" of cross-flow drying is apparent from Fig. 8. This non-uniformity of MCs within the rice deep-bed range could be quantified using the "range of MCs within the bed", defined as the difference of final MCs of rice in baskets B1 and B10, respectively (Fig. 2). For a particular drying duration, the range of MCs within the rice bed decreased with increasing Q. For example, when 20.5%-IMC rice was dried for 30 min using 57°C/13% RH drying air at 0.36 $(m^3/s)/m^2$, the range of MCs within the column was between 15.5 and 19.9% (4.4 PPs) (Fig. 8A). But when Q was increased to 0.46 $(m^3/s)/m^2$, the range of MCs within the column decreased to 15.4 to 19.7% (4.3 PPs). When Q was increased to 0.56 $(m^3/s)/m^2$, this range decreased to 14.8 to 18.5% (3.7 PPs). Similar trends occurred across the 60- and 90-min drying durations for the 20.5%-IMC rice.

While the final MCs were much less in Fig. 8B versus those in Fig.8A owing to the difference in the rice IMCs, the general trends of decreasing MCs with increasing Q were true. Additionally, the range of MCs for the 16.3%-IMC rice were less than those for the 20.5%-IMC rice, indicating that with all other drying conditions remaining the same, the non-uniformity of drying decreased with decreasing IMCs; this may have implications on the HRY of the rice exiting from the drying column after a drying pass.

These MC results also revealed that even for a typical 12.5 - 13.0% bulk-column MC, there is severe over-drying of the rice kernels located adjacent to the HAP (Fig. 8). For example, when 16.3%-IMC rice was dried to 12.7% bulk-column MC after 60 min using 0.46 $(m^3/s)/m^2$ (Table 1), rice located in the first fiber-mesh basket, B1 (nearest to the HAP) had a MC of only 11.1% (Fig. 8B; 60-min plot). Since, the depth of each basket was 3.8 cm, it is likely that the rice kernels immediately adjacent to the HAP were severely over-dried to MCs of 5 to 6%. Similar results were obtained in another study as well.[39]

The general trends suggested that the effect of Q was more prominent for the greater rice-IMC (20.5%) than that compared to a lesser rice-IMC (16.3%); the MC lines for the different levels of Q were farther apart when 20.5%-IMC rice was dried than those when 16.3%-IMC rice was dried using the same drying air condition (Fig. 8). This shows that the rice-IMC impacts the effect of Q on the rice MC profiles (Fig. 8), as well as the drying air profiles (Figs. 4, 5, 6, and 7).

Intra-kernel material state gradients. To study the effect of Q in creating different extents of intra-kernel material state gradients in a cross-flow drying column, which in turn, is hypothesized to affect fissuring and consequent breakage in rice kernels, the hypothetical "drying trajectory" of the rice in each fiber-glass basket was plotted on the "material state diagram for rice".[40] This was accomplished by pictorially estimating the "position" of the baskets during drying using the procedure described in a previous study.[39]

As with the visualizations in the above-mentioned study,[39] two considerations are relevant. First, although the average MC and grain temperature of the bulk rice in the baskets were used to establish the "position" of the baskets on the state diagram before and after drying, in reality, there is a tremendous range in MCs of individual rice kernels that constitute a bulk of rice kernels.[39] As a result of this, kernels constituting the bulk actually have different "drying trajectories" and thus, kernels have different extents of material state gradients created within them. The second consideration is that the "Tg line"[40] is in fact a band of temperatures, and that the "boundary" between the glassy and rubbery regions is not as well-defined as depicted in Figs. 9 and 10.

It is worth mentioning that although conceptually, the rice kernel temperature ought to be plotted on the state diagram, the small size of the rice kernel makes it extremely difficult to accurately measure grain temperature, especially in a deep-bed study like this one, hence, grain temperatures were not measured. Yet, since it is known that temperature equilibrium between the kernels and the drying medium is easily attained,[6] the temperature reading of the drying air recorded by the T/RH sensors was taken as a close approximation of the grain temperature, as was also done in another study.[37]

Figs. 9 and 10 show the bulk average MCs and grain (drying air) temperatures of selected baskets. For each IMC, the bulk IMC and the average grain temperature of 20.5°C were plotted on the state diagram for each drying duration/Q combination. Then, the bulk MCs and grain temperatures of the rice in baskets B1, B2, B3, B5, B7, and B10 after the indicated drying durations were plotted. Hypothetical "drying trajectories" were drawn for the rice in B1 and B10 to show the material state transitions that occurred during drying.

Although the points showing the bulk MC and temperature give the average conditions of kernels in the respective baskets, fissuring and resultant HRY reduction during the drying process is actually dependent upon the extent of material state gradients formed inside the kernels, which in turn, is dependent on the drying air condition. At a given drying air T/RH combination, the surface of the kernel attains equilibrium with the drying air soon after drying commences, but the interior volumes of the kernel do not, this creates intra-kernel MC gradients and consequently, intra-kernel material state gradients. The greater the severity of the drying air condition, with correspondingly lesser associated rough rice equilibrium MC, the greater the extent of intra-kernel material state gradients formed.

A study in which the T/RH of the drying air was set at four levels but all drying runs were conducted at one drying duration and one level of Q[39] reported that with increasing severity of the drying air condition (increasing temperature and decreasing RH), greater extents of intra-kernel material state gradients were formed, which resulted in greater amounts of fissuring and consequent breakage.

However, in the present study, the inlet drying air T/RH, and consequently, the rough rice equilibrium MC was the same throughout the experiment. Despite this, the extents of intra-kernel material state gradients were found to be a function of both Q and drying duration. Across IMCs, at the same drying duration, more rice baskets “transitioned” from the glassy to the rubbery region with increasing Q. Likewise, at the same Q, more baskets “transitioned” with increasing drying duration (Figs. 9 and 10). Thus, with either drying duration or Q held constant, increasing the level of the other parameter led to the creation of greater material state gradients within the kernels. This was because even at the same drying air T/RH, increasing Q, but keeping drying duration constant, increased heat and mass transfer between the drying air and the rice kernel, which subsequently resulted in greater volumes of the kernel periphery transitioning from the glassy to the rubbery region, and thus establishing greater material state gradients within the kernel. Similarly, at a constant Q, increasing drying duration allowed for the creation of greater intra-kernel material state gradients. Given the relationship between increased intra-kernel material state gradients to fissuring and consequent breakage, it is expected that for a particular drying air condition wherein the majority of the kernels transitioned from the glassy to the rubbery state during drying, increasing Q and(or) drying duration could negatively impact HRYs.

The “non-uniformity” of cross-flow drying as mentioned above (Fig. 8) is also apparent from the state diagrams in Figs. 9 and 10. Increases in both Q and drying duration led to a decrease in the range of MCs within the column, i.e., drying became more uniform throughout the deep-bed of rice. Moreover, when IMC of the rice decreased, the effect of Q as well as drying duration on the non-uniformity of drying decreased. Thus, from a T_g perspective, the extents of intra-kernel material state gradients created were dependent on the drying air condition, Q, drying duration, and the IMC of the rice.

CONCLUSIONS

This study measured the drying air and rice MC profiles inside an experimentally-simulated cross-flow drying column, as a function of drying duration using two IMCs of long-grain rice for three air flow rates, for a typical drying air T/RH condition used in such dryers. Additionally, this study estimates the extents of intra-kernel material state gradients created when different levels of Q, drying duration, and rice IMC are used, which are known to impact fissuring and consequent HRY reductions. In addition to providing data that can be used for validation of mathematical models predicting: 1) drying air T/RH as it passes through a deep-bed of rice in a cross-flow drying scenario, 2) resultant MCs of the rice as a function of distance from the HAP, and 3) the extents of intra-kernel material state gradients created, these data show the impact of Q during the cross-flow rice drying process. Thus, the results obtained in this study could potentially be used to identify the levels of Q required in cross-flow rice dryers to increase energy efficiency of the drying process, while maintaining HRYs and dryer throughput; this will eventually contribute towards improved dryer design and better process control.

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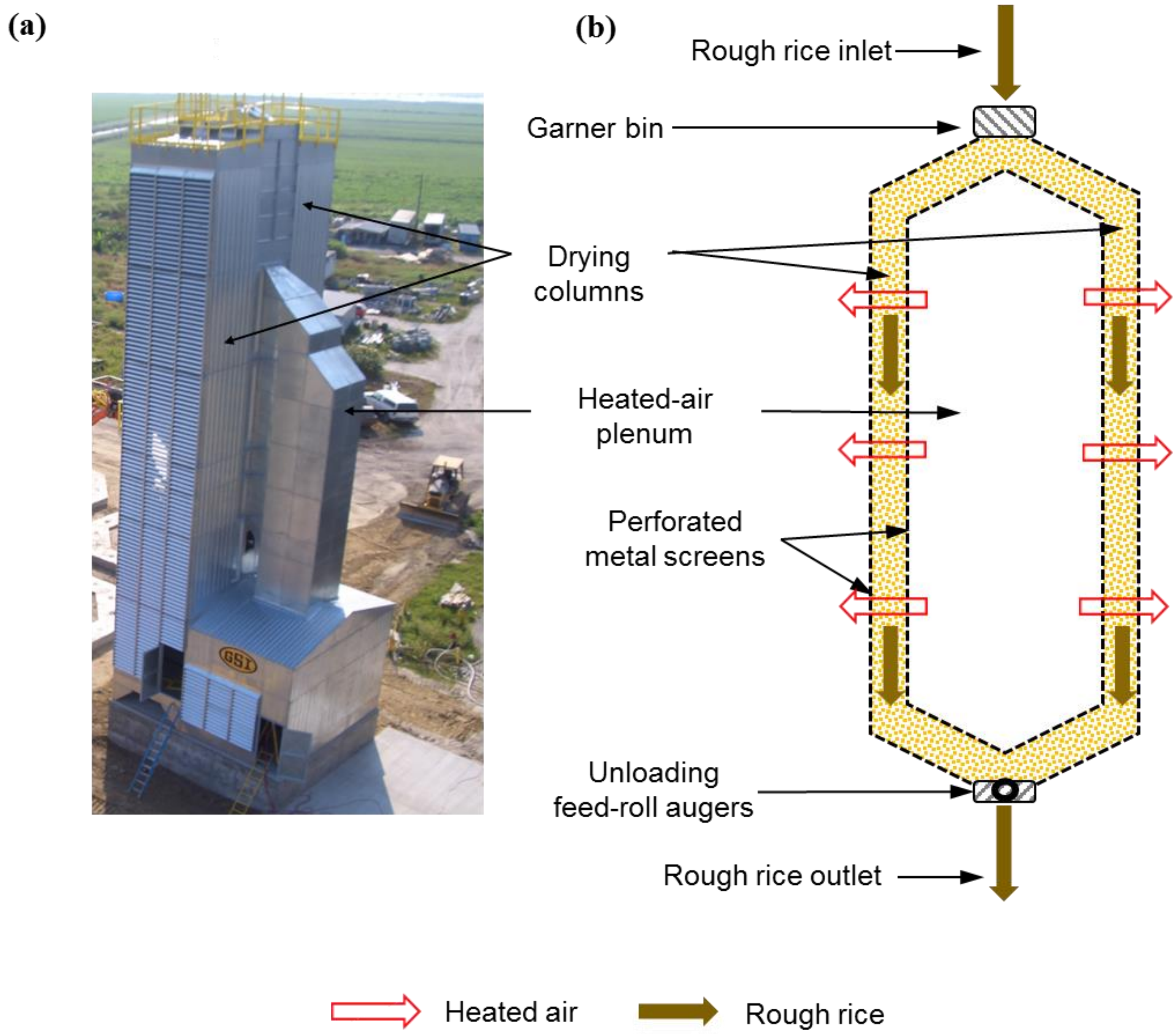

Fig. 1: (a) Photograph of a commercial cross-flow dryer and (b) schematic of a cross-flow dryer showing "cross-wise" direction of movement of rough rice and heated air.[37]

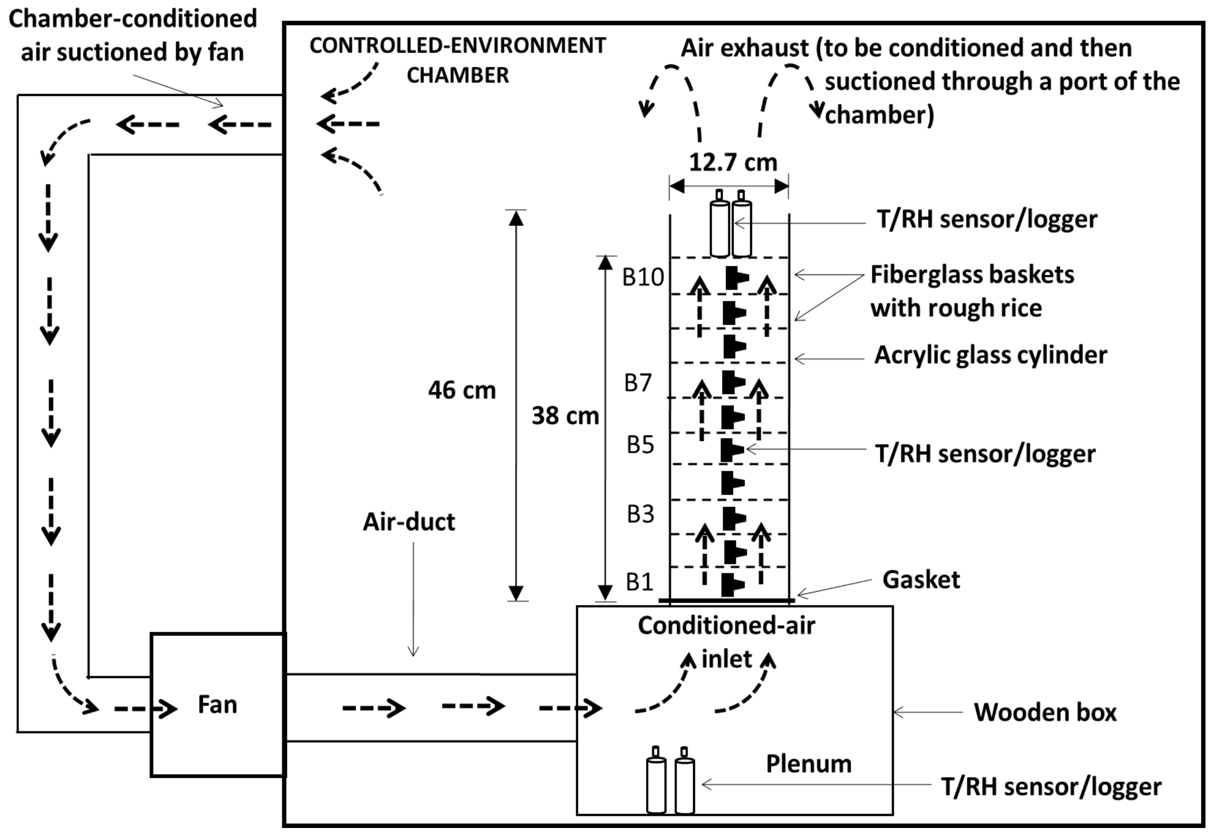

Fig. 2: Schematic diagram of the drying system. The drying assembly comprised a wooden box, an acrylic glass drying column with a metallic screen base, and a set of ten, fiber-mesh cylindrical baskets filled with rough rice and temperature/relative humidity (T/RH) sensors/loggers, all positioned inside a controlled-environment chamber.[39]

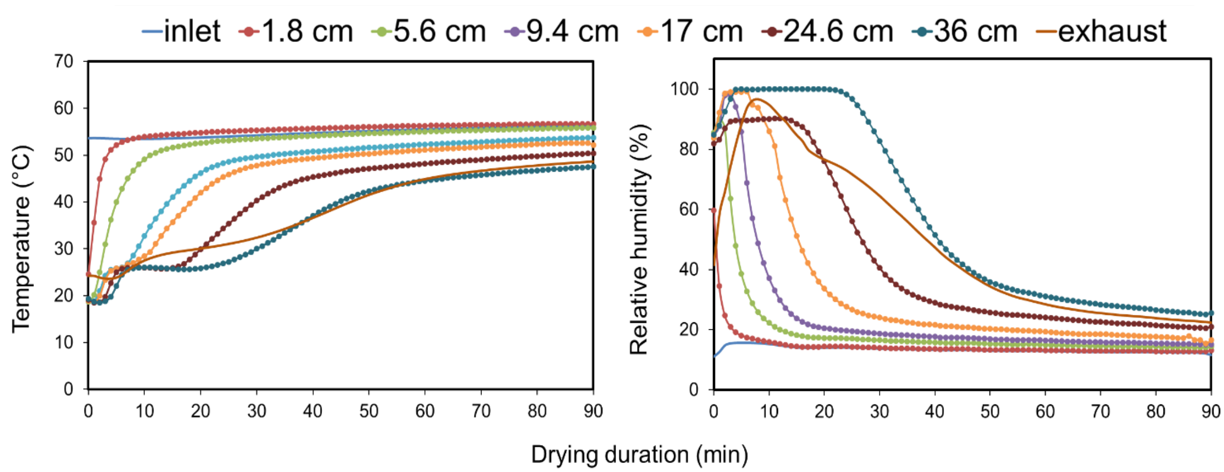

Fig. 3: Temperature and relative humidity profiles at the indicated distances from the heated-air plenum when rough rice at 20.5% initial moisture content (wet basis) was dried for 90 min using 57°C/13% RH air at an airflow rate of 0.46 $(m^3/s)/m^2$. Data points are the mean values of 18, 12, and 6 drying runs for the 30-, 60-, and 90-min drying durations, respectively.

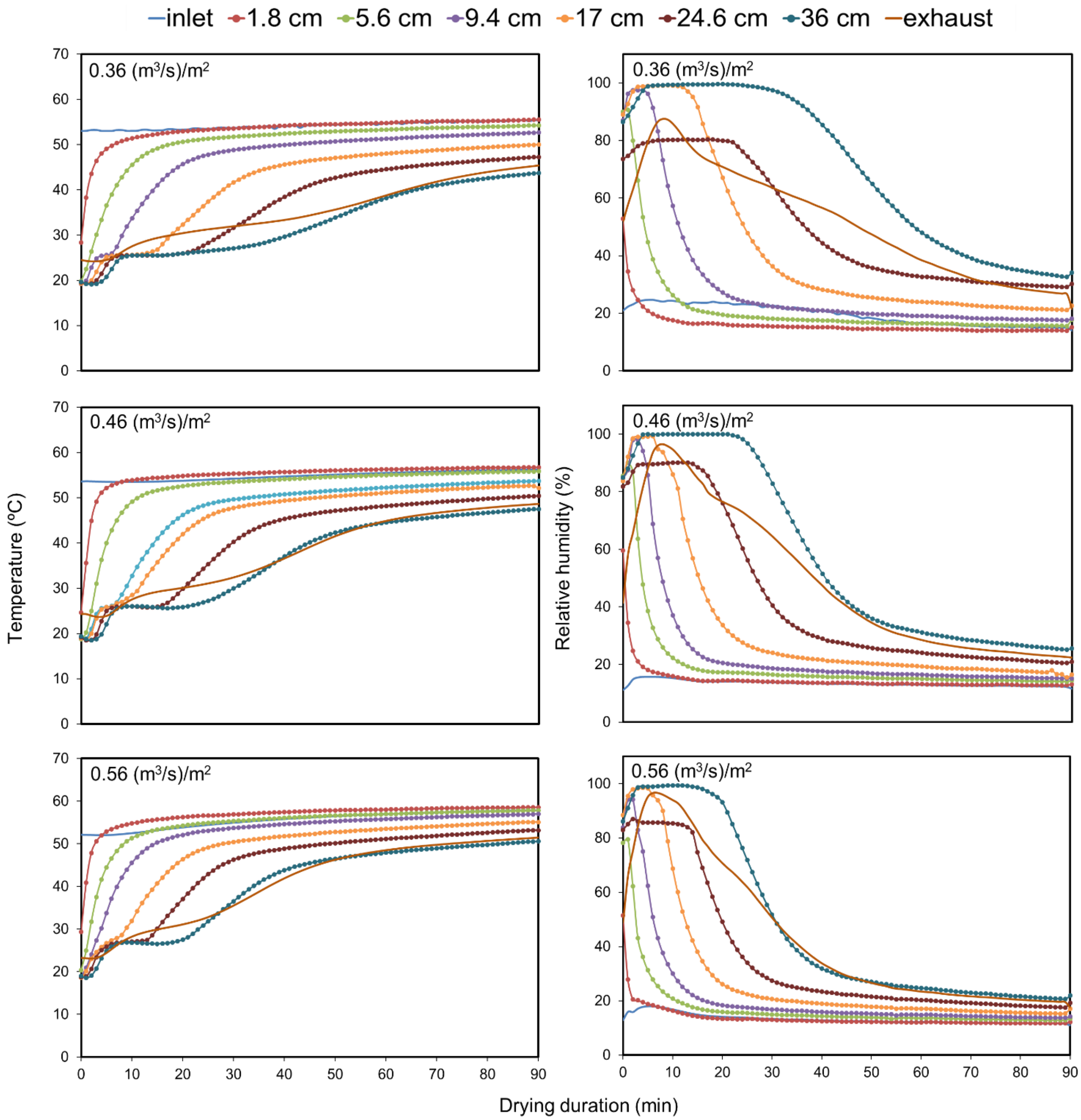

Fig. 4: Temperature and relative humidity profiles at the indicated distances from the heated-air plenum when rough rice at 20.5% initial moisture content (wet basis) was dried for 90 min using 57°C/13% RH air at the indicated airflow rates. Data points are the mean values of 18, 12, and 6 drying runs for 30-, 60-, and 90-min drying durations, respectively.

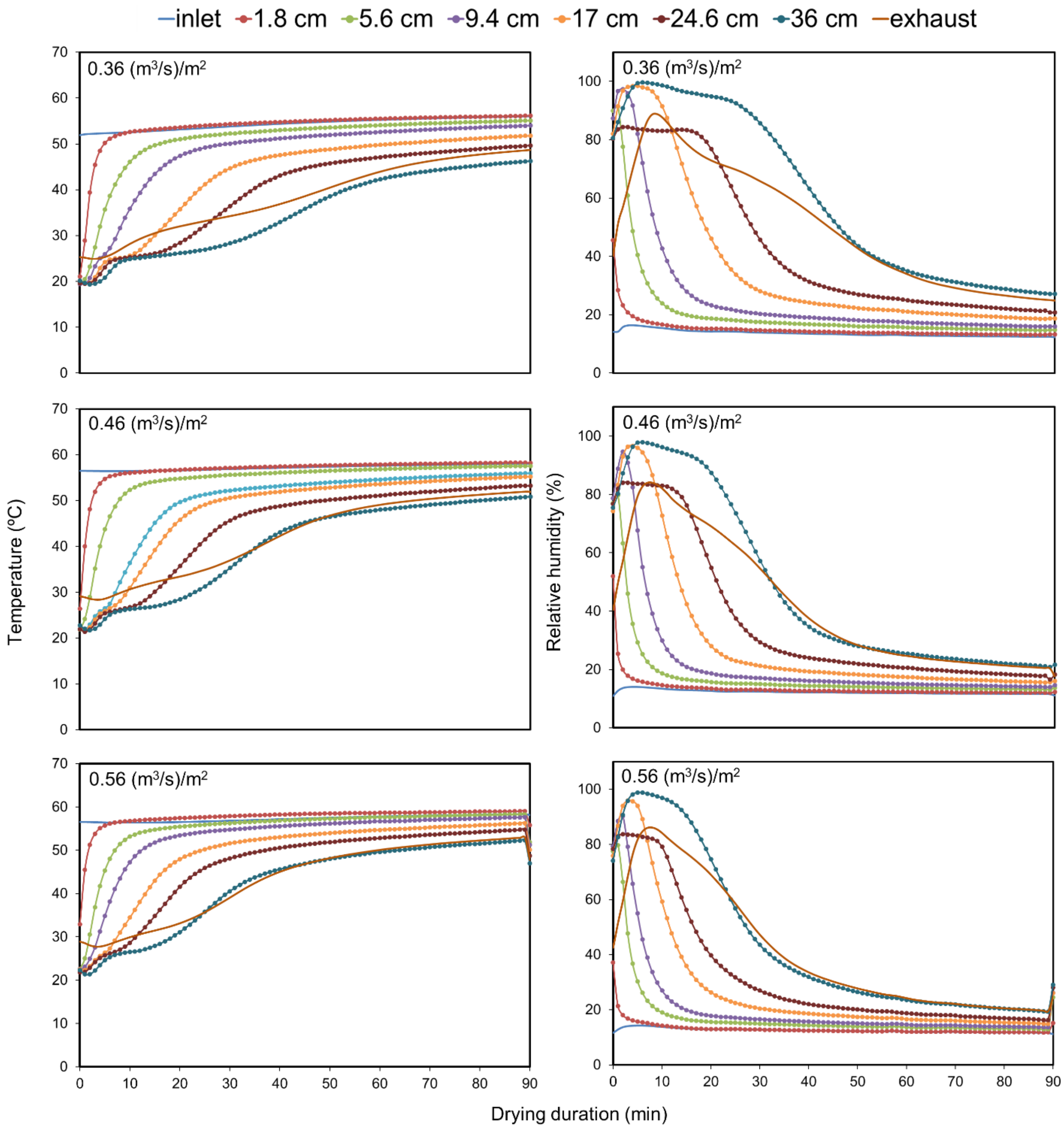

Fig. 5: Temperature and relative humidity profiles at the indicated distances from the heated-air plenum when rough rice at 16.3% initial moisture content (web basis) was dried for 90 min using 57°C/13% RH air at the indicated airflow rates. Data points are the mean values of 18, 12, and 6 drying runs for 30-, 60-, and 90-min drying durations, respectively.

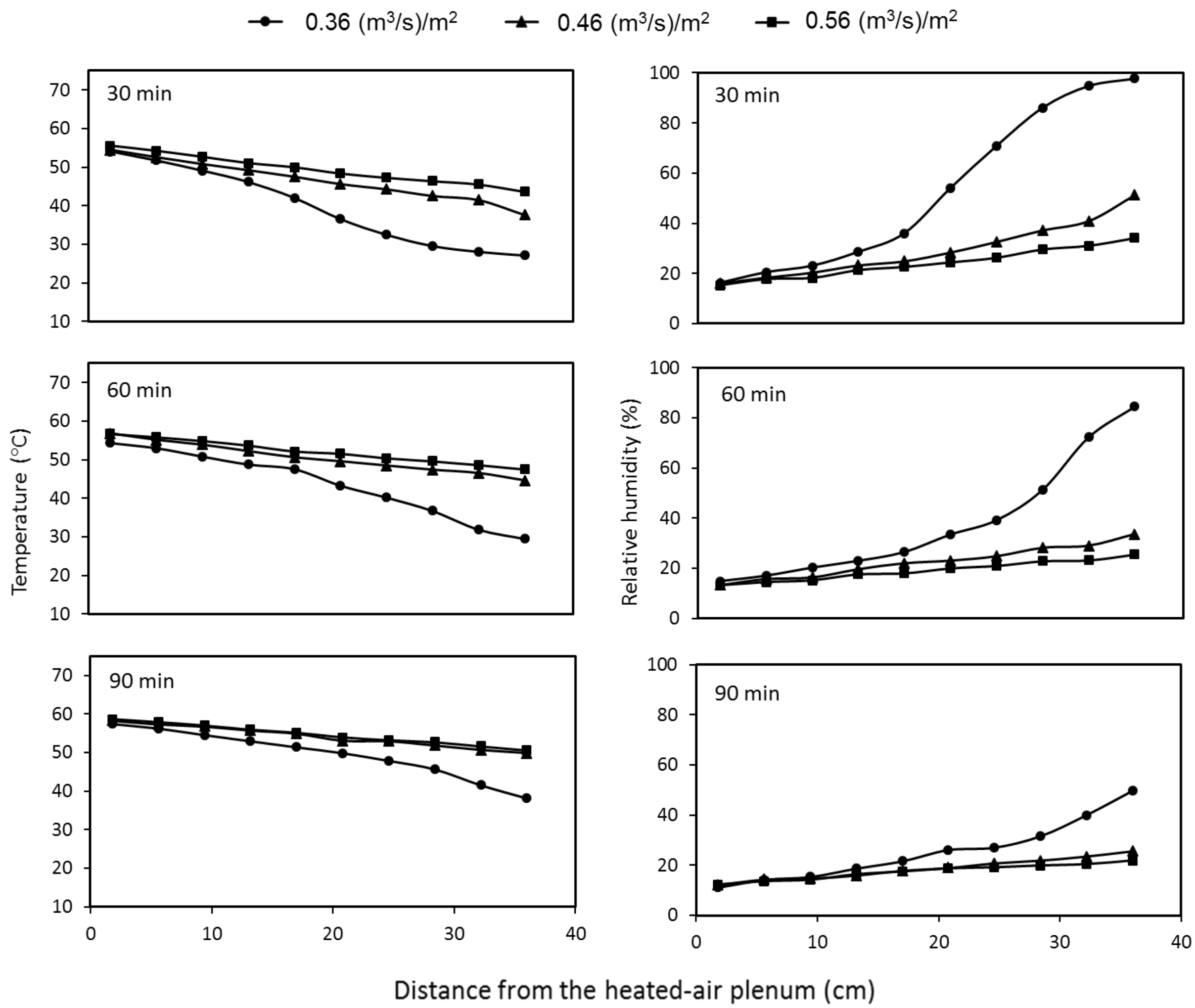

Fig. 6: Temperature and relative humidity profiles with distance from the heated-air plenum after drying a 38-cm thick rice-bed for 30, 60, and 90 min. Rough rice at 20.5% initial moisture content (wet basis) was dried using 57°C/13% RH air at the indicated airflow rates. Data points are the mean values of 18, 12, and 6 drying runs for 30-, 60-, and 90-min drying durations, respectively.

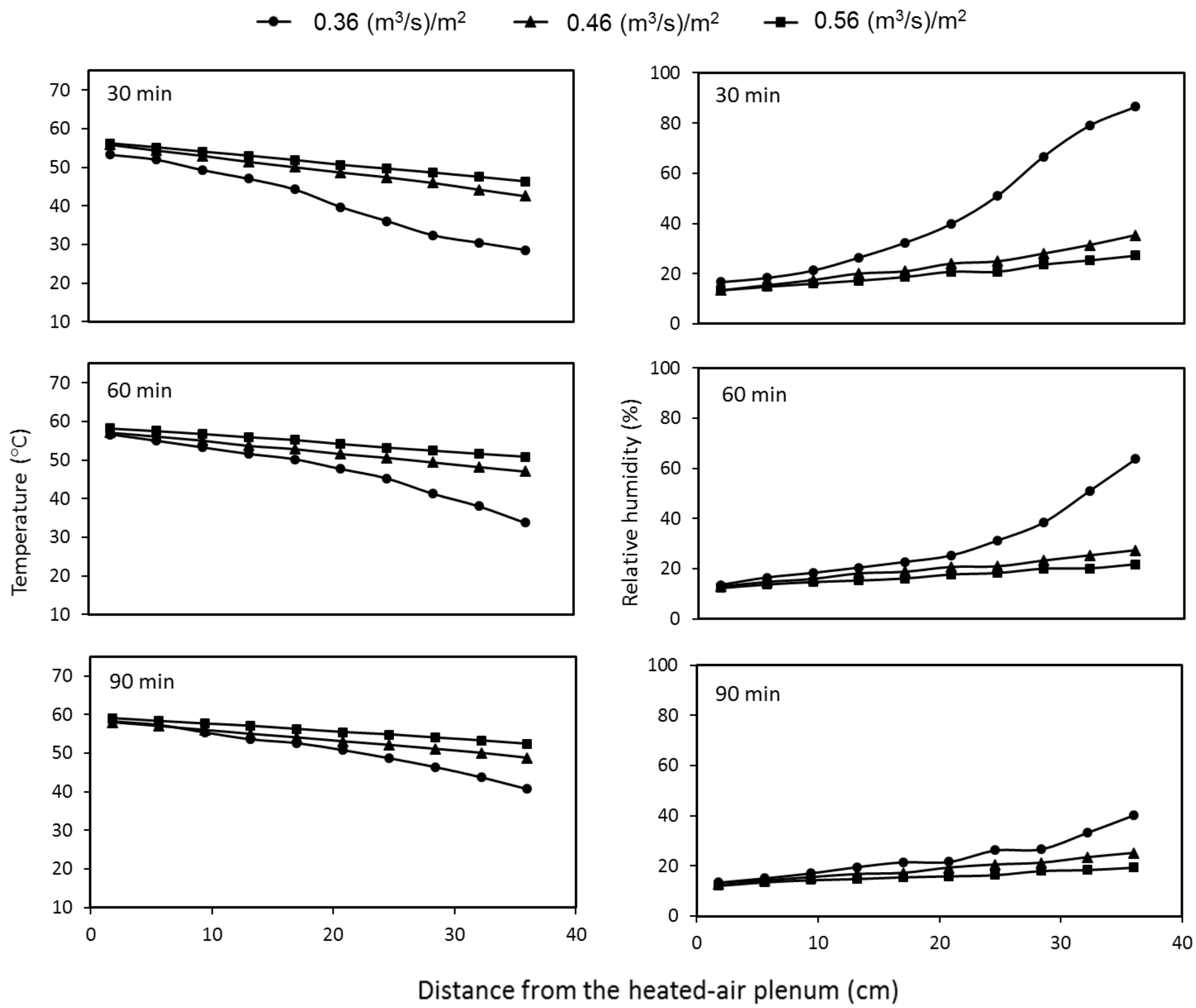

Fig. 7: Temperature and relative humidity profiles with distance from the heated-air plenum after drying a 38-cm thick rice-bed for 30, 60, and 90 min. Rough rice at 16.3% initial moisture content (wet basis) was dried using 57°C/13% RH air at the indicated airflow rates. Data points are the mean values of 18, 12, and 6 drying runs for 30-, 60-, and 90-min drying durations, respectively.

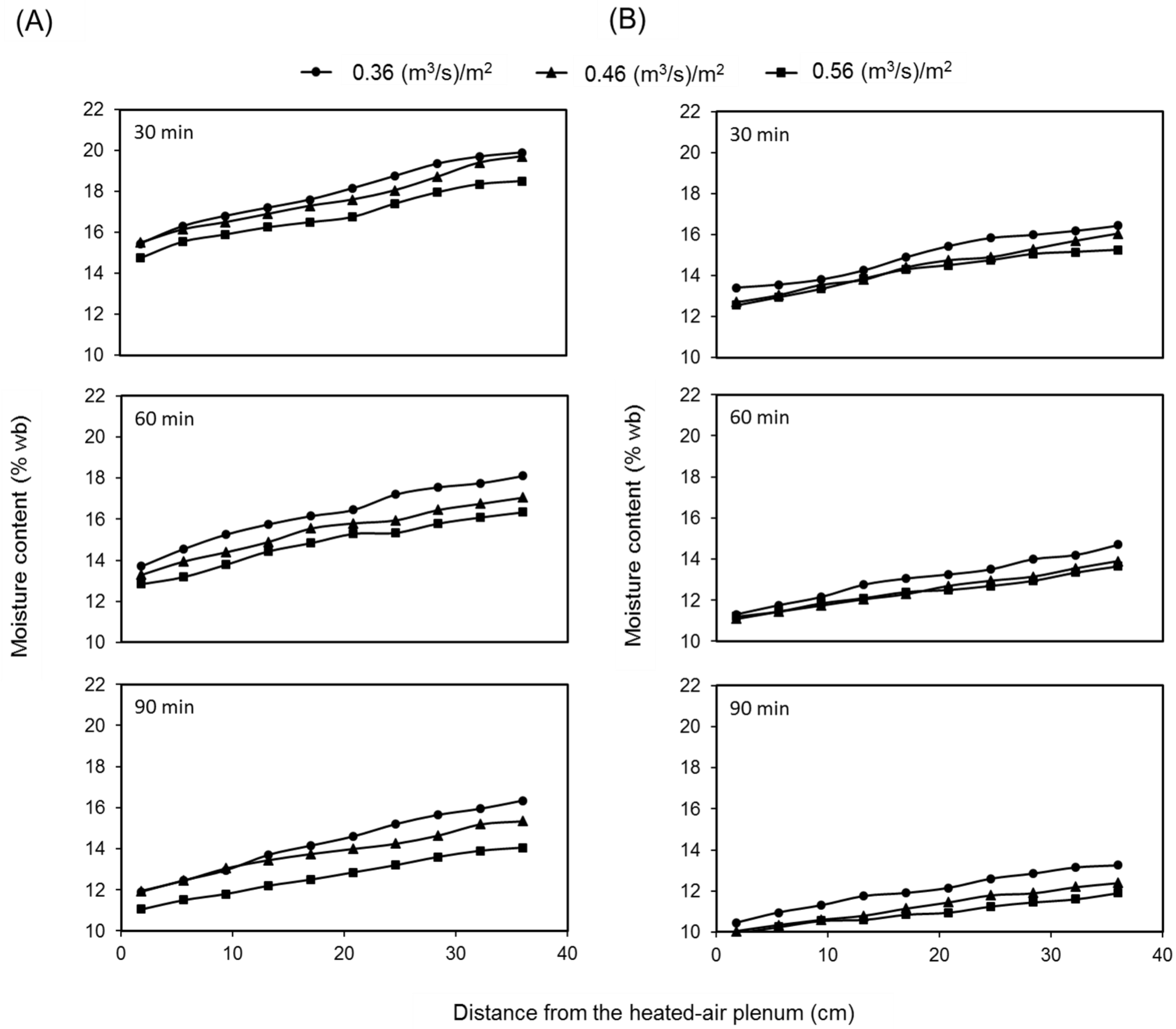

Fig. 8: Final moisture contents (MCs) as a function of distance from the heated-air plenum after drying rough rice at (A) 20.5% and (B) 16.3% initial MCs (wet basis), respectively, for 30, 60, and 90 min using 57°C/13% RH air at the indicated airflow rates. Data points are the mean values of two experimental treatment replications.

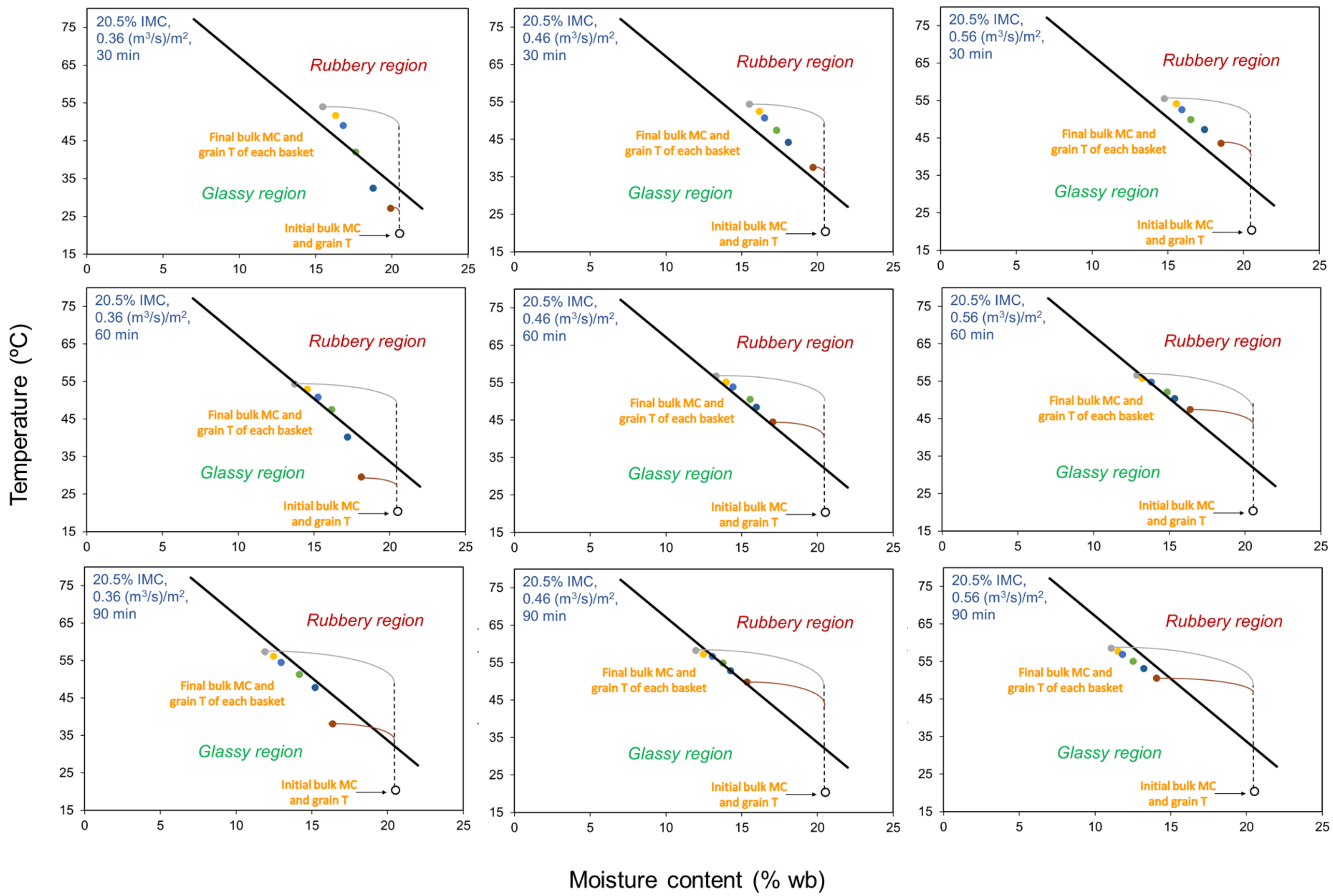

Fig. 9: Initial and final bulk-grain state points of baskets B1 (nearest to the heated-air plenum), B2, B3, B5, B7, and B10 shown on a state diagram[40] along with the “trajectory” of the bulk grain during drying when rough rice at 20.5% initial moisture content (IMC) (wet basis) was dried using 57°C/13% RH air at airflow rates of 0.36, 0.46, or 0.56 $(m^3/s)/m^2$ for 30, 60, or 90 min. Data points are the mean of two experimental treatment replications.

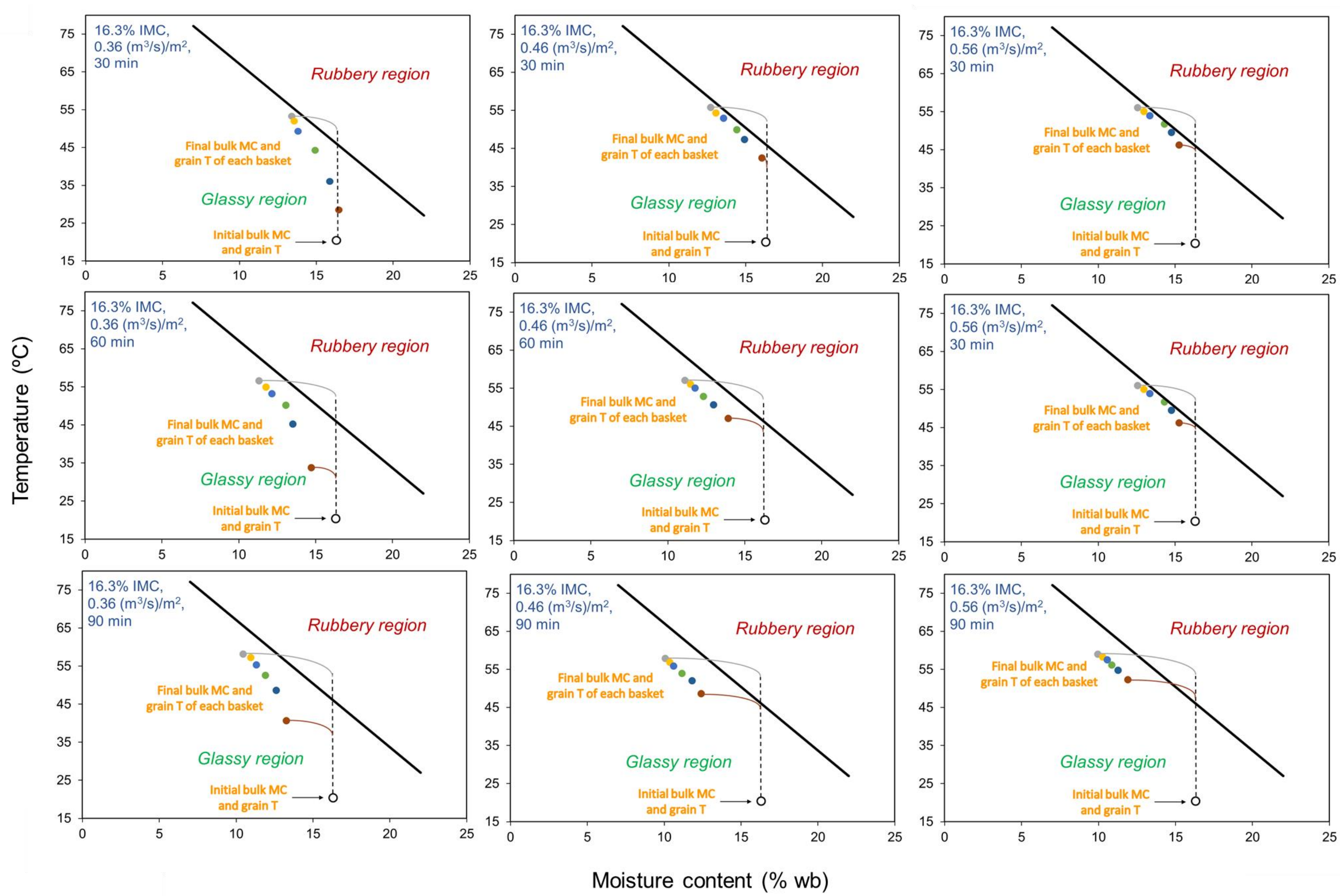

Fig. 10: Initial and final bulk-grain state points of baskets B1 (nearest to the heated-air plenum), B2, B3, B5, B7, and B10 shown on a state diagram[40] along with the “trajectory” of the bulk grain during drying when rough rice at 16.3% initial moisture content (IMC) (wet basis) was dried using 57°C/13% RH air at airflow rates of 0.36, 0.46, or 0.56 $(m^3/s)/m^2$ for 30, 60, or 90 min. Data points are the mean of two experimental treatment replications.

Table 1: Final bulk-column moisture contents (MCs) after drying rough rice at 20.5% and 16.3% initial MCs for 30, 60, and 90 min, respectively, using 57°C/13% RH air at the indicated airflow rates. Data are the mean of two experimental treatment replications.

Initial MC (% wet basis)	Drying duration (min)	Final MCs (% wet basis) after drying at the indicated airflow rates; percentage point moisture content reduction (PPMR) in parenthesis*		
		Airflow rate $(m^3/s)/m^2$		
		0.36	0.46	0.56
20.5	30	17.9 (2.6)	17.6 (2.9)	16.8 (3.7)
	60	16.2 (4.3)	15.4 (5.1)	14.8 (5.7)
	90	14.3 (6.2)	13.8 (6.7)	12.7 (7.8)
16.3	30	15.9 (0.4)	14.6 (1.7)	14.4 (1.9)
	60	12.9 (3.4)	12.7 (3.6)	12.6 (3.7)
	90	12.3 (4.0)	11.3 (5.0)	11.0 (5.3)

*Percentage point difference between initial MC and final MC

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III. CHAPTER 2

Effect of Tempering Approach Following Cross-flow Drying on Rice Milling Yields

ABSTRACT

Different tempering approaches were followed after drying rough rice at 20.5% and 16.3% initial moisture contents using 57°C/13% RH air at an airflow of 0.56 $(m^3/s)/m^2$ for 30, 60, and 90 minutes in an experimentally-simulated cross-flow drying column. Head rice yields (HRYs) were consistently lesser when the interstitial air from rice from different cross-sections of the drying column was allowed to "interact" during tempering than when the rice from these different cross-sections was tempered separately. As a means to avoid HRY reduction, minimum tempering durations were estimated to allow the subsidence of drying-induced intra-kernel material state gradients.

INTRODUCTION

In the Mid-South region of the United States of America (USA), rough rice is harvested at moisture contents (MCs) ranging between 14% to 22% wet basis (wb) and dried to ~ 12.5% MC (wb) for safe storage. Rough rice is then dehulled and typically milled before consumption. Milled rice comprises "whole, intact" kernels called head rice, which is defined as milled kernels that are at least three-fourths of the original kernel length,[1] and broken kernels. "Milling yield" refers to either or both the milled rice yield (MRY) and the head rice yield (HRY), defined as the mass of milled rice and head rice, respectively, expressed as a percentage of the original, dried rough rice mass.[1] Because of the economic importance of head rice relative to broken kernels, the broad objective in any rice drying operation is to maximize HRY.

Rice kernel fissures are fractures of the endosperm that can either be "cross-wise/perpendicular" to the long-axis of the rice kernel[2] or in no specific alignment.[3] Since fissuring is considered to be a key factor contributing to rice kernel breakage and consequent reduction in HRY, rice producers and processors aim to minimize fissuring. Fissuring in rice kernels can occur because of several reasons, including rapid moisture adsorption by low-MC kernels,[4,5] and improper drying and post-drying/tempering processes.[6-8] The extent of fissuring depends on several factors, including cultivar and varietal differences,[9,10] rice grain dimensions, especially the length-to-width ratio of kernels,[11,12] and other physicochemical properties.[12,13]

In the case of heated-air drying, fissuring in rice kernels during the "drying process", which comprises drying as well as tempering, has been hypothesized to occur primarily due to intra-kernel differences in starch properties due to portions of the kernel being above and below the "glass transition temperature (T_g)".[7,14] The T_g is a MC-dependent material property that determines whether a material is in a "rubbery" or "glassy" state, i.e., above or below, respectively, the T_g line of a material state diagram for rice.[15] According to the T_g hypothesis,[7] owing to the temperature and MC distribution of the rice kernels, intra-kernel material state transitions from the glassy to the rubbery state, and vice versa, can occur during the drying process. Depending upon the relative volumes of glassy and rubbery regions created within a kernel, the kernel may fissure from intra-kernel stresses resulting from the vastly different physical and mechanical properties of these two regions.

Typically, rough rice is dried from harvest MC to storage MC using several alternating drying and tempering passes. In the USA, drying is commonly accomplished in cross-flow column dryers using elevated air temperatures ranging from 40°C to 70°C to achieve high throughput rates. In such dryers, rice flows vertically downward between two metal screens, which form the grain column, whereas heated air flows through the grain column in a direction perpendicular (or "cross-wise) to that of the grain movement. Typically, ambient air is first forced into the dryer by an axial or centrifugal fan, then heated by a burner using direct combustion of natural gas or propane, before entering the heated-air plenum (HAP) of the dryer. Unloading feed-roll augers, located at the bottom of the dryer columns, meter the rice out of the dryer.

Tempering is a standard practice in the rice drying process that offers several advantages. Tempering allows intra-kernel material state gradients, which are typically created during heated-air drying, to subside.[7,16] Because these gradients are allowed to subside, fissuring and consequent HRY reductions are prevented; this has been demonstrated in several "thin-layer" drying studies[7,8] and in one "deep-bed" study.[17] Tempering at elevated temperatures has been shown to minimize fissuring[6,12,18-21] and maximize HRYs.[7,8,19-21,22-26] Several studies[7,19,20,26,27] have also shown that for heated-air drying, tempering at the drying air temperature for a "sufficient duration" was required for intra-kernel material state equilibration and in turn, for maintaining HRYs; some studies[8,21,28] also showed that tempering at elevated temperatures decreased required tempering durations. An additional advantage of tempering is that it decreases the total drying duration[19,20,29] by improving the drying rate in subsequent drying passes,[30,31] thereby increasing overall energy efficiency.[32]

Previous research on tempering conditions included a wide range of tempering temperatures and corresponding durations for a range of rice initial MCs (IMCs) to maintain HRYs.[7,8,21,22,28,33,34] While it is known that tempering in the rubbery region, i.e., at a temperature $> T_g$, reduces fissuring, the length of the duration required for "sufficient tempering" is still not clearly known. The recommendations for "sufficient tempering durations" from the studies cited above were based upon stationery-bed, “thin-layer” drying tests; a thin-layer is defined as a layer of particles whose depth must not exceed three layers of particles.[35] In the case of rough rice, this layer is ~ 0.6 cm in depth/thickness. But in reality, rice is not dried in “thin-layers” in commercial systems, but as “deep-beds”, with typical thicknesses of the drying column in cross-flow dryers varying between 25 cm and 45 cm. Moreover, in commercial and on-farm dryers, rice from a column cross-section is mixed as it exits the dryer and thus, the effect of tempering all the rice together in bulk may be different from that reported in thin-layer drying tests. The effect of tempering a “deep-bed” of rice was not found in the literature.

Additionally, it would be valuable to understand the extent of fissure occurrence when rice from different cross-sections of a cross-flow dryer, i.e., rice located at different distances from the HAP, is removed and tempered separately. This understanding could be used to design better cross-flow rice dryers and thus, to improve the rice drying process.

The present study was conducted with the goal of understanding the effect of post-drying tempering approaches/mthods on milling yields and the extent of fissure occurrence when rice from different dryer cross-sections was tempered in different ways. Because the drying treatment is very important in creating intra-kernel material state gradients, which the tempering process is intended to subside, it was deemed critical that the tempering treatments be conducted using rice that had been immediately prior-dried in a system representative of commercial drying systems. As such, rice for this study was dried within a drying column that was designed to simulate a cross-flow drying action; the system is described herein and reported previously.[17] The objectives of this study were to: (1) elucidate the effect of tempering approaches on milling yields of rice that had been immediately prior-dried in a system representative of cross-flow drying systems, (2) investigate the effect of rice IMCs and drying duration on these milling yields, and (3) for each tempering approach, estimate the minimum tempering duration required to minimize HRY reduction.

MATERIALS AND METHODS

Overview of the experiment. Drying was conducted in a specially-designed apparatus and each drying treatment was followed by one of three post-drying tempering approaches. Rough rice at two IMCs (20.5% and 16.3%) was dried using 57°C/13% RH air at an airflow rate of 0.56 $(m^3/s)/m^2$ for three drying durations (30, 60, or 90 min), thereafter, the rice was tempered using one of the three approaches described below. Each drying condition/tempering approach treatment was replicated twice, thus yielding 36 drying/tempering runs (2 IMCs X 1 drying air T/RH X 1 airflow rate X 3 drying durations X 3 tempering approaches X 2 replications).

Sample procurement and preparation. A 600-kg bulk lot of rough rice (long-grain cultivar Roy J) was combine-harvested at the University of Arkansas Rice Research & Extension Center, Stuttgart, AR, USA in September, 2015 at 23.2% MC. The lot was cleaned using a dockage tester (XT4, Carter-Day, Minneapolis, MN, USA) to remove foreign material and unfilled kernels. The bulk lot was divided into two 300-kg sub-lots, which were gently conditioned to approximately 21% and 16% MC, respectively, using air at 26°C/56% RH, and stored in sealed containers at 4°C for 4 months. Immediately prior to drying treatments, the rice MC was determined to be 20.5% and 16.3%, respectively, by drying duplicate, 15-g sub-samples in a convection oven (1370FM, Sheldon Manufacturing Inc., Cornelius, OR, USA) maintained at 130°C for 24 h.[36]

Experimental system. Drying runs were accomplished inside a 0.91-m^3, controlled-environment chamber (Platinous Sterling Series, ESPEC North America, Hudsonville, MI, USA) that was capable of producing drying air at 57°C/13% RH, with a corresponding rough rice equilibrium MC of 6.4% (wet basis), calculated using the Modified Chung-Post equation.[37] This air condition is typical for use in cross-flow dryers in the Mid-South region of the USA. During operation, a centrifugal fan (4C108, Dayton Electric Manufacturing Co., Niles, IL, USA), coupled to a 0.56-kW electric motor (3N443BA, Dayton Electric Manufacturing Co., Niles, IL, USA), suctioned air at the desired temperature/RH (T/RH) from the chamber through a port located in the front door of the chamber, and then forced the air through a side-wall port in the chamber wall to a drying assembly (Fig. 1). A variable-frequency drive (AF-300 Mini, GE Fuji Drives USA Inc., Salem, VA, USA) was connected to the fan motor to achieve the desired airflow rate.

The drying assembly (Fig. 1) comprised a wooden box that served as a HAP, an acrylic glass drying column with a metal screen base, and a set of ten, fiber-mesh cylindrical baskets (3.8-cm deep, 12.7-cm diameter). The fiber-mesh baskets were used as "sample holders" and enabled the drying column to be divided into discrete layers, thus permitting sampling at various distances from the HAP. Each basket had a fiber-mesh flap on top that could be fastened using metal pins, and a fiber-mesh handle to facilitate dismantling after the completion of a drying run.

Drying procedure. Approximately 2.7 kg of rough rice was removed from cold storage, placed in a sealed bag and equilibrated to room temperature (22°C) for 24 h prior to each drying run. Each of the ten baskets was filled with 270 g of rough rice. A T/RH sensor/logger (UX100-011, Onset Corporation, Bourne, MA, USA; accuracy: ±0.21°C and 2.5% RH) was placed inside each basket to measure air conditions every 60 s during drying. Stacking the ten baskets in the acrylic glass cylinder resulted in a 38-cm deep rice column. Additionally, four T/RH sensors, as shown in Fig. 1, were utilized; two were placed inside the HAP and two at the top of the rice column to record air conditions at the column inlet and exhaust, respectively. When the controlled-environment chamber stabilized at the T/RH setting for a drying run, the chamber door was opened for < 1 minute to position the rice column on the HAP. After the desired drying duration, the drying column was dismantled.

Tempering conditions. For all tempering approaches, a tempering temperature of 60ºC and a duration of 4 h were selected; the reasons for selecting these conditions are as follows.

Air at 57°C/13% RH was used to dry the 20.5%- and 16.3%-IMC rice for 30, 60, and 90 min; according to the T_g hypothesis described above, for these rice MC/temperature combinations, most of the rice kernels would transition into the rubbery region during drying. It was deemed necessary that tempering be conducted in the rubbery region as well, i.e. at a temperature > T_g. Thus, regardless of the tempering approach followed, rice was tempered inside a pre-heated oven that was maintained at 60ºC, (T_g for 20.5%- and 16.3%-IMC rice are 32°C and 46°C, respectively[15]) ensuring that the rice was "held in the rubbery region" or "above the T_g line" to allow the intra-kernel state gradients that had developed during drying to subside sufficiently before subsequent cooling.

A preliminary experiment was conducted to determine the tempering duration required at the 60ºC tempering temperature for the developed intra-kernel material state gradients to subside sufficiently. The 20.5%- and 16.3%-IMC rice lots were dried using 57°C/13% RH air at an airflow rate of 0.56 $(m^3/s)/m^2$ for the longest drying duration (90 min) used in this study, using the procedure described above; these drying conditions would create the maximum extents of material state gradients within the rice kernels. After each drying run, the drying column was dismantled and the contents of all ten baskets were mixed, then, a 500-g sample was placed into a sealed bag and placed in the pre-heated oven at 60ºC for different durations (1 to 8 h, at 1-h increments). Following a given tempering duration, the sample was conditioned to 12.5% MC in a chamber maintained at 26°C/56% RH and milled per the procedure described below. Eight drying runs were conducted for each rice-IMC level (1 drying run for each tempering duration), with 2 replications, thus resulting in 32 drying runs (2 IMCs X 8 drying runs X 2 replications). Exponential functions were used to describe the relationship between HRY and tempering duration; from these curves, it was found that HRYs stabilized after ~ 3 h of tempering for both rice IMCs. A previous study[16] reported that all moisture gradients were eliminated after about 4 h of tempering at 50ºC after drying short-grain rough rice for 1 h using 50ºC/60% RH air. Thus, the tempering duration was set to 4 h for this study.

Tempering approaches. In commercial and on-farm cross-flow dryers, rice flows downward through the drying columns and feed-roll augers meter the dried rice out of the columns. Thus, the rice from a column cross-section is mixed as it exits the dryer. In order to simulate this experimentally, after the drying column (Fig. 1) was dismantled following a drying run, the rice from all ten baskets was mixed together, then a 500-g sample was placed into a sealed bag and kept in the pre-heated oven (60ºC) for 4 h. A T/RH sensor, which had been pre-programmed to record T/RH conditions every 60 s, was also placed inside the mass of rice in the sealed bag. After the 4-h duration, the sample was spread into a thin-layer on a screened tray and conditioned to 12.5% MC to conduct a milling analysis (described below). This tempering approach (designated as TA1; Fig. 2a) was thus expected to be representative of the mixing that rice undergoes during the drying process in an actual cross-flow dryer.

It was also desired to quantify the milling yield of rice located at various distances from the HAP if that rice were tempered separately after each drying treatment; for this, TA2 was followed (Fig. 2b). In TA2, after the drying column was dismantled following a drying run, each basket was kept intact and placed into an individual sealed bag. The T/RH sensors inside the baskets during drying continued to record T/RH conditions every 60 s during tempering. After the ten bags were tempered inside the 60ºC oven for 4 h, the contents of each basket were separately conditioned to 12.5% MC and milled. These data would be representative of the milling yields of layers of rice located at specific distances from the HAP during drying and then tempered separately.

Additionally, it was desired to elucidate, during tempering, the "interaction effect" of the interstitial air from rice dried at different cross-sections of the drying column on the respective milling yields of the rice located at those cross-sections. To simulate this scenario, TA3 was followed (Fig. 2c); the ten baskets were kept intact to preserve their identity as separate milling samples, but all the baskets were placed together inside one individual sealed bag, thus allowing the interstitial air from each of the baskets to interact/mix. Immediately after placing the ten baskets in the bag, the bag was placed inside the 60ºC-oven for 4 h. Following the 4-h duration, the contents of each basket were separately conditioned to 12.5% MC and milled. Similar to the situation in TA2 described above, the T/RH sensors inside the baskets during the drying treatment continued to record T/RH conditions every 60 s during the tempering duration. Using this method, TA3 built upon TA2, in that the milling yield of rice as a function of distance from the HAP was produced, but in TA3, the interstitial air from different layers in the drying column (or baskets) was allowed to "interact", whereas in TA2, the contents of each basket were kept autonomous during tempering. For all tempering treatments, the T/RH sensors were retrieved after each drying/tempering run and the data downloaded.

It must be noted that in TA1, a 40-g sample was also collected from the mixed mass, allowed to equilibrate in a sealed plastic bag at 22°C for 48 h, and the MC measured following the above oven-drying procedure to indicate the final average MC of the column. Additionally, it was desired to quantify the MC of rice in each basket after a given drying treatment. To do this, a separate drying run was conducted using the same drying air conditions but following that drying run, the rice from each basket was preserved as separate samples; a 40-g sample was taken from each basket for oven MC analysis immediately after drying to indicate the final MC as a function of distance from the HAP.

Milling analyses. TA1, in which the rice from all ten baskets was mixed, yielded one milling sample, while TA2 and TA3, in which baskets were kept separate, each yielded ten milling samples per drying/tempering treatment. However, for the individual baskets, it was reasoned that the milling yields of baskets B1, B2, B3, B5, B7, and B10 (Fig. 1) would provide sufficient trends across the rice column. Hence, for each drying/tempering treatment combination, 13 milling samples were produced per experiment replication (1 from TA1 + 6 from TA2 + 6 from TA3). With a total of 6 drying combinations (2 IMCs X 1 drying air T/RH X 1 airflow rate X 3 drying durations), 13 milling samples per drying combination, and 2 replications, 156 samples were milled.

For each milling analysis, a 150-g rough rice sample was dehulled using a laboratory huller with a clearance of 0.048 cm between the rollers (THU-35A, Satake Engineering Co., Ltd., Tokyo, Japan). The brown rice was then milled for 19 s (previously determined as the milling duration required to achieve 0.4% surface lipid content) using a laboratory mill (McGill No. 2, Rapsco, Brookshire, TX, USA) with a 1.5-kg mass placed on the lever arm 15 cm from the center of the milling chamber. A sizing device (61, Grain Machinery Manufacturing Co., Miami, FL, USA) was then used to separate head rice from broken kernels. Milling yield was quantified as MRY and HRY.

Statistical analyses. Using JMP Pro software (Version 13.0.0, SAS Institute, Inc., Cary, NC, USA), non-linear model fitting was performed on the RH data recorded by the T/RH sensors during the 4-h tempering duration.

RESULTS AND DISCUSSION

General layout. Since the primary goal of this study was to develop a better understanding of the effect of tempering approach on milling yield, for both IMCs and across all drying durations, the milling yields from the three tempering approaches are presented. Following this, the responses from the T/RH sensors that were placed inside the sealed bag(s) during tempering for each tempering approach are discussed; however, for ease of understanding, only the data from the 60-min drying runs are presented.

Final bulk-column moisture contents. When 20.5%-IMC rice was dried using 57°C/13% RH air at 0.56 $(m^3/s)/m^2$ for 30, 60, and 90 min, the final bulk-column MCs, with the associated percentage point moisture content reductions (PPMRs), were 16.8% (3.7 PPMR), 14.8% (5.7 PPMR), and 12.7% (7.8 PPMR), respectively, whereas when 16.3%-IMC rice was dried using the same air conditions, the corresponding final bulk-column MCs for 30, 60, and 90 min were 14.4% (1.9 PPMR), 12.6% (3.7 PPMR), and 11.0% (5.3 PPMR), respectively. Thus, for the same drying duration, rice at a greater IMC underwent a greater PPMR than rice having a lesser IMC. This can be explained in terms of the total energy required to dry rice from a given IMC to a desired final MC.[38] According to that study, the total heat of desorption of rice (Q_t) is a function of rice MC and kernel temperature; at a given kernel temperature, Q_t decreases exponentially as MC increases. Thus, the energy required to remove a unit mass of water from rice is less when the rice is at a greater IMC than that when the rice is at a lesser IMC, indicating that water is increasingly bound to the rice matrix as IMC decreases. In other words, for the same energy supplied, rice at a greater IMC (20.5%) will dry more, i.e., have a greater PPMR, than rice at a lesser IMC (16.3%).

Milling yields from the three tempering approaches. For both rice IMCs, no significant differences were obtained in MRYs (data not shown) across all drying condition/tempering approach treatments, thus the following discussion is limited to HRYs.

Fig. 3 shows the HRY trends after tempering (per the three tempering approaches as listed in Fig. 2) immediately prior-dried rice lots at the 20.5% and 16.3% IMCs using 57°C/13% RH drying air at 0.56 $(m^3/s)/m^2$ for 30, 60, and 90 min. The HRYs from TA1 in Fig. 3 are represented by a solid green line since TA1 yielded only one composite milling sample from the 38-cm deep drying column (Fig. 2a), but TA2 and TA3 yielded 6 milling samples each; thus, the data points shown in Fig. 3a and 3b for TA2 and TA3 represent HRYs as a function of distance from the HAP.

Fig. 3 shows that for both IMCs, HRYs from TA1 progressively decreased with increasing drying duration. For example, for the 20.5%-IMC rice, HRYs of the bulk column after drying for 30, 60, and 90 min were 55.6%, 54.0%, and 48.3%, respectively (Fig. 3a), and for the 16.3%-IMC rice, HRYs were 55.0%, 54.5%, and 50.4%, respectively (Fig. 3b). Additionally, these data show that for the 90-min drying duration, the 20.5%-IMC rice had a lesser bulk-column HRY than that of the 16.3%-IMC rice.

The HRYs obtained from TA2 are those of rice samples that were dried at different cross-sections of the drying column, i.e., at different distances from the HAP, immediately prior to being tempered separately or autonomously (Fig. 2b). For both rice IMCs, HRYs of separately tempered rice samples that were prior-dried at different distances from the HAP, were quite stable for the shortest drying duration of 30 min. For example, when 20.5%-IMC rice was dried for 30 min and then tempered as separate samples, the range of HRYs obtained across the drying column was narrow (1.2 percentage points (PPs)); HRYs were between 53.7% at B1 (1.8 cm from the HAP) and 54.9% at B10 (36 cm from the HAP) (see Fig. 1 and Fig. 3 for equivalence between "drying basket number" and "distance from the HAP"). But as the drying duration increased to 60 min and then to 90 min, HRYs obtained after tempering were much less for samples that had been situated near the HAP during drying than those situated farther into the drying column (Fig. 3a and 3b). For example, for the 90-min drying duration, the range of HRYs within the drying column was significantly greater (11.9 PPs); HRYs were 42.8%, 45.9%, 49.3%, 52.9%, 54.2%, and 54.7% in B1, B2, B3, B5, B7, and B10, respectively. These results are believed to be due to the development of greater intra-kernel material state gradients in the rice located near the HAP during drying.

Fig. 3 also shows the effect of IMC on HRY reductions of rice samples that were tempered separately immediately after being dried at different distances from the HAP; this was particularly true for samples that were located near the HAP when drying was conducted for 60 and 90 min. Although the general trend of rice near the HAP incurring severe HRY reductions was true for both rice IMCs when the baskets were tempered separately following a drying run (TA2; per Fig 2(b)), the severity of HRY reduction was less for the 16.3%-IMC rice than the 20.5%-IMC rice (Fig. 3). For example, when 20.5%-IMC rice was dried for 60 min, the HRY of B1 (1.8 cm from the HAP) was 49.0% whereas when 16.3%-IMC rice was dried for the same duration, the HRY of the same basket was 52.6%. Similarly, when 20.5%-IMC rice was dried for 90 min and tempered as separate samples at 60ºC for 4 h, the HRY of B1 was 42.8% whereas when 16.3%-IMC rice was dried for the same duration and tempered, HRY of the same basket was 50.1%. These results are believed to be due to the development of greater intra-kernel material state gradients in the greater IMC-rice during drying, which in turn led to greater fissuring and increased HRY reductions.

As discussed earlier, TA3 was conducted to elucidate the “interaction effect” of the interstitial air from rice samples that had been prior-dried at different cross-sections of the drying column, on the respective milling yields of the rice located at those cross-sections, hence; all the baskets were kept intact but were tempered together in one sealed bag (Fig. 2c). Interestingly, near the HAP, samples located at the same cross-section of the drying column during drying but tempered per TA3 following drying, generally had lesser HRYs (or greater HRY reductions) than those tempered per TA2. Although similar results were obtained for both rice-IMCs, this effect was more prominent for the 20.5%-IMC rice. Additionally, this effect was more prominent when longer drying durations of 60 and 90 min were used. For example, after drying 20.5%-IMC rice for 60 min, the HRY of B1 was 47.0% when TA3 followed drying, but the HRY of the same basket was 2.0 PPs greater, at 49.0%, when TA2 followed drying. Similarly, the HRY of B2 was 49.3% when TA3 followed drying, but it was 2.0 PPs greater, at 51.3%, when TA2 followed drying.

Because the rice and drying conditions were the same throughout the drying runs, further decreases in HRYs of the corresponding baskets when TA3 was followed after drying were speculated to have occurred because of the tempering approach used in that case. HRYs were consistently lesser when the interstitial air from the rice from different cross-sections of the drying column was allowed to “interact” during tempering (TA3) than when the air from rice from these different cross-sections was tempered separately (TA2). These results showed that in addition to the HRY reductions in samples tempered per TA2, which were due to intra-kernel material state gradients formed during drying, additional reductions in HRYs of the corresponding samples tempered per TA3 were due to the “interaction effect” of the interstitial air from rice from each dryer cross-section during the tempering stage. Thus, HRYs obtained from TA3 yielded a unique insight into the tempering process and confirmed the importance of the tempering approach in impacting HRYs.

It may be mentioned here that owing to the design of TA3 in this study, rice kernels from each basket (i.e. each cross-section of the drying column) could not truly “mix” with kernels from other baskets (i.e. other cross-sections of the drying column) since basket-entities had to be preserved for HRY determinations, rather, only the interstitial air from the each of the baskets got mixed, which resulted in the additional HRY reductions in samples located near the HAP during drying. Hence, it can be conjectured that this “interaction effect” would perhaps be more intense and result in severe HRY reductions in rice located near the HAP in an actual cross-flow dryer where rice kernels from all the column cross-sections actually get mixed and exit the dryer as a single mass. Depending on the severity of HRY reduction in the rice located near the HAP, this could potentially decrease the HRY of the mixed mass of rice.

Fissure counts. Although it is well-established that kernel fissuring is responsible for HRY reductions, a “fissure count”-analysis was performed on the rice samples using an X-ray system (UltraFocus 60, Faxitron Bioptics LLC., 100 Tucson, AZ, USA). The settings of the system were selected per the recommendations of a previous study[39]; 5 sets of 20 rough rice kernels were observed per X-ray image at 3X magnification per replication (100 kernels per replication), with a total of three replications (300 kernels) per drying/tempering treatment. As an example of the overall trends, Fig. 4 shows the fissured kernels (%) of 20.5%-IMC rice samples that were tempered per the three tempering approaches described in Fig. 2, after being prior-dried using 57°C/13% RH drying air at 0.56 (m^3/s)/m^2 for 60 min. As expected from the HRY trends, more fissuring and consequent breakage occurred in the samples which were located near the HAP during drying. Additionally, for the same drying treatment, tempering per TA3 resulted in greater percentages of fissured kernels than tempering per TA2, thus, confirming that the additional HRY reductions in case of TA3 was due to the interaction effect of the interstitial air from the rice from different distances from the HAP. These "fissure-count" trends were consistent across all drying/tempering treatments.

T/RH responses during tempering. Fig. 5a shows the T/RH response of the sensor during the 4-h tempering duration when rice was tempered per TA1 (all baskets mixed during tempering), after 20.5%-IMC rice was prior-dried using 57°C/13% RH drying air at 0.56 (m^3/s)/m^2 for 60 min. The final MC after the 60-min drying duration was 14.8% (5.7 PPMR). The increase in the T/RH reading of the sensor from 30ºC/76% RH to 60ºC/90% RH during the 4-h duration is explained as follows. After a drying run, it took ~ 2 min to dismantle the drying column, mix the rice from the ten baskets together and place the rice mass in a sealed bag, along with a pre-programmed T/RH sensor. The sensor was at room temperature (~ 22ºC) until it was placed inside the bag of rice, so once it was inside the bag, it started recording the temperature of the interstitial air (30ºC). As tempering progressed, the sensor's temperature reading increased, because it was placed inside the sealed bag of rice which in turn, was kept inside the 60ºC-oven. On the other hand, the RH reading of the sensor progressively increased throughout the tempering duration because moisture continued to diffuse from the interior to the peripheral regions of the rice kernels and then, evaporate into the interstitial air.

Fig. 5b shows the T/RH response of the sensor as in Fig. 5a except that the IMC of the rice was 16.3%, and the final MC of rice was 12.6% (3.7 PPMR). Although the temperature curve in Fig. 5b was very similar to the corresponding curve in Fig. 5a, the RHs recorded for the 16.3%-IMC rice (Fig. 5b) throughout the tempering duration were much less than those for the 20.5%-IMC rice (Fig. 5a). This was expected since kernels in the 16.3%-IMC rice lot had reached an average final bulk MC of only 12.6% and thus had lesser amounts of water that evaporated into the interstitial air during the tempering duration.

A previous study[40] defined and predicted "tempering index (I_c)" of corn kernels using the surface liquid concentration of those kernels. Thereafter, another study[28] used changes in the RH of the interstitial air of short-grain rough rice kernels to predict changes in the surface liquid concentration and re-defined the tempering index in terms of RH as shown in Eq. (1).

$$I_{RH} = \frac{RH\ (t) - RH\ (t=0)}{RH\ (t=\infty) - RH\ (t=0)} \qquad \text{…Eq. (1)}$$

where:

I_{RH} is the tempering index in terms of RH of the interstitial air,

RH at time (t) = 0 is the RH at the start of tempering, and the RH at $t = \infty$ refers to the maximum RH obtained in the void space during tempering.

These studies[28,40] calculated the "tempering index" as a means to predict the minimum tempering duration required for adequate tempering to have occurred. Two degrees of tempering were considered in the study conducted on rough rice kernels,[28] the first being "complete tempering" or I_{RH} = 1.0, and the second being "95% tempering" or I_{RH} = 0.95. Then, the durations required to attain these two degrees of tempering were calculated.

In the present study, a similar approach was followed to estimate the "minimum tempering duration ($t_{0.95}$)" required; in case of each tempering approach, this was done using the RH profiles of the interstitial air during tempering. The "fit curve" platform in the statistical package JMP Pro was used to fit several non-linear models on the RH data (Fig. 5a). A mechanistic growth model was determined to be the best fit for the RH curves; as indicated by their low root mean square error (RMSE) and R-Square (R^2) values. For the 20.5%-IMC rice, the RMSE and R^2 values were 0.37 and 0.99, respectively (Fig. 5a). This model estimated that upon complete tempering (I_{RH} = 1.0), the RH of the interstitial air would be asymptotic at 91.4% RH (95% confidence interval (C.I.) = 91.3% to 91.5% RH). Then, the "inverse prediction" on the "fit curve" platform on JMP Pro was used to estimate that the tempering duration required for "95% tempering to be complete" (I_{RH} = 0.95); $t_{0.95}$ was calculated to be 144 min. Following a similar procedure for the 16.3%-IMC rice (RMSE and R^2 values for the model fit were 0.44 and 0.99, respectively), the asymptotic RH was 71.9% RH (C.I. = 71.8% to 72.0% RH) and $t_{0.95}$ = 144 min.

Thus, it was estimated that if 16%- to 20%-IMC long-grain rough rice were dried using the above-mentioned drying conditions, ~ 144 min was required for the intra-kernel material state gradients developed during drying to subside sufficiently so that no additional fissuring and consequent HRY reduction would occur during tempering, given that tempering was conducted at 60ºC. Results from the preliminary experiment (described above) showed that HRYs stabilized ~ 3 h. Interestingly, the $t_{0.95}$ estimate of 144 min (2 h 20 min) obtained using non-linear model fitting was very close to the 3-h duration predicted in the preliminary experiment. In fact, the preliminary experiment comprised 90-min drying runs whereas the data in Fig. 5 were from 60-min drying runs; this meant that the 90-min drying runs had greater extents of intra-kernel material state gradients developed during drying and thus expectedly required a longer duration (~ 3h) for the subsidence of those gradients, as compared to the shorter duration required (2 h 20 min) for the subsidence of the gradients developed in the shorter 60-min drying duration.

The $t_{0.95}$ estimate obtained in this study is more relevant in the current United States (US) rice drying industry because of two reasons: 1) in the present study, rice was prior-dried in a cross-flow drying column representative of those used in commercial systems as opposed to being prior-dried as a "thin-layer" (3-cm deep) in the previous study,[28] and 2) the rice used was a long-grain variety, "Roy J" whereas the previous study[28] used a short-grain variety, "S6"; this is particularly important because 71% of the US rice production comprised long-grain varieties during the 2012 - 2016 period.[41]

Fig. 6 shows the T/RH profiles as a function of tempering duration for baskets B1, B2, B3, B5, B7, and B10 when TA2 and TA3 were followed after immediately prior-drying 20.5%-IMC rough rice using 57°C/13% RH drying air at 0.56 $(m^3/s)/m^2$ for 60 min. Mechanistic growth models were fit on the RH data using the same procedure described above; for both tempering approaches, as distance from the HAP increased (i.e., from B1 to B10), the asymptotic RH progressively increased (Table 1). This was expected; the interstitial air in B1 had the minimum asymptotic RH because the rice inside that basket had dried the most whereas the interstitial air in B10 had the maximum asymptotic RH because the rice in that basket had dried the least. However, a comparison between the estimates of the asymptotic RH values from the corresponding baskets for the two tempering approaches showed that these asymptotic RH values were not significantly different, implying that even if baskets were kept together in one sealed bag per TA3, the interaction effect of the interstitial air was not statistically distinguishable using only the RH data, yet, the interaction effect was distinguishable from the HRY data (Fig. 3).

Additionally, Table 1 shows that for corresponding baskets tempered per TA2 and TA3, the $t_{0.95}$-trends were exactly opposite to the asymptotic RH trends; $t_{0.95}$ decreased with increasing distance from the HAP (Table 1). These $t_{0.95}$ results from the respective baskets confirmed that with decreasing extents of intra-kernel material state gradients being created during drying, shorter tempering durations will suffice. Table 1 also shows the same overall trends with respect to the asymptotic RH and corresponding $t_{0.95}$ values for the 16.5%-IMC rice. However, for corresponding baskets, the asymptotic RHs were less when the rice IMC was less (16.5%), showing that for the same drying air conditions tested, $t_{0.95}$ was dependent on the rice IMC.

CONCLUSIONS

The following conclusions were drawn from this study:

1. For both rice IMCs, no significant differences were obtained in MRYs across all drying condition/tempering approach treatments. However, significant differences were obtained in case of HRYs.
2. When rice samples were tempered separately after being prior-dried at different cross-sections of the drying column (TA2), post-tempering HRYs at different cross-sections of the column were quite stable for the shortest drying duration of 30 min. But for the 60- and 90-min durations, HRYs obtained after tempering were much less for samples that had been situated near the HAP during drying than those situated farther into the drying column. Additionally, the severe decreases in HRYs in the rice located near the HAP were the primary reason for the overall decrease of the bulk-column HRYs.

3. For the same rice and drying conditions, post-tempering HRYs were consistently lesser when the interstitial air from rice from different cross-sections of the drying column was allowed to “interact” during tempering (TA3) than when the interstitial air from rice from these different cross-sections was tempered separately (TA2). These results showed that in addition to the HRY reductions that occurred due to the development of intra-kernel material state gradients during drying, additional reductions in HRYs of the corresponding samples tempered per TA3 were due to the “interaction effect” of the interstitial air from rice from each dryer cross-section during tempering, thus confirming the importance of the tempering approach in impacting HRYs.
4. For each tempering approach, the minimum tempering duration ($t_{0.95}$) required for the subsidence of drying-induced intra-kernel material state gradients was determined using non-linear model fitting on the RH data of the interstitial air from rice recorded during tempering. Results showed that 144 min of tempering was required when 16%- to 20%-IMC long-grain rough rice was dried in the drying assembly described above using 57°C/13% RH air at an airflow rate of 0.56 $(m^3/s)/m^2$ for 60 min, and then tempered together per TA1 (all baskets mixed) inside a 60ºC-oven for 4 h. The same procedure was used to estimate $t_{0.95}$ for rice located in each cross-section of the drying column.

The post-tempering HRYs obtained in this study can be used for validation of mathematical models predicting HRY profiles in cross-flow rice drying scenarios. The knowledge gained herein regarding the effect of tempering approach following cross-flow drying on milling yields can be used to design better cross-flow rice dryers and thus, to improve the rice drying process.

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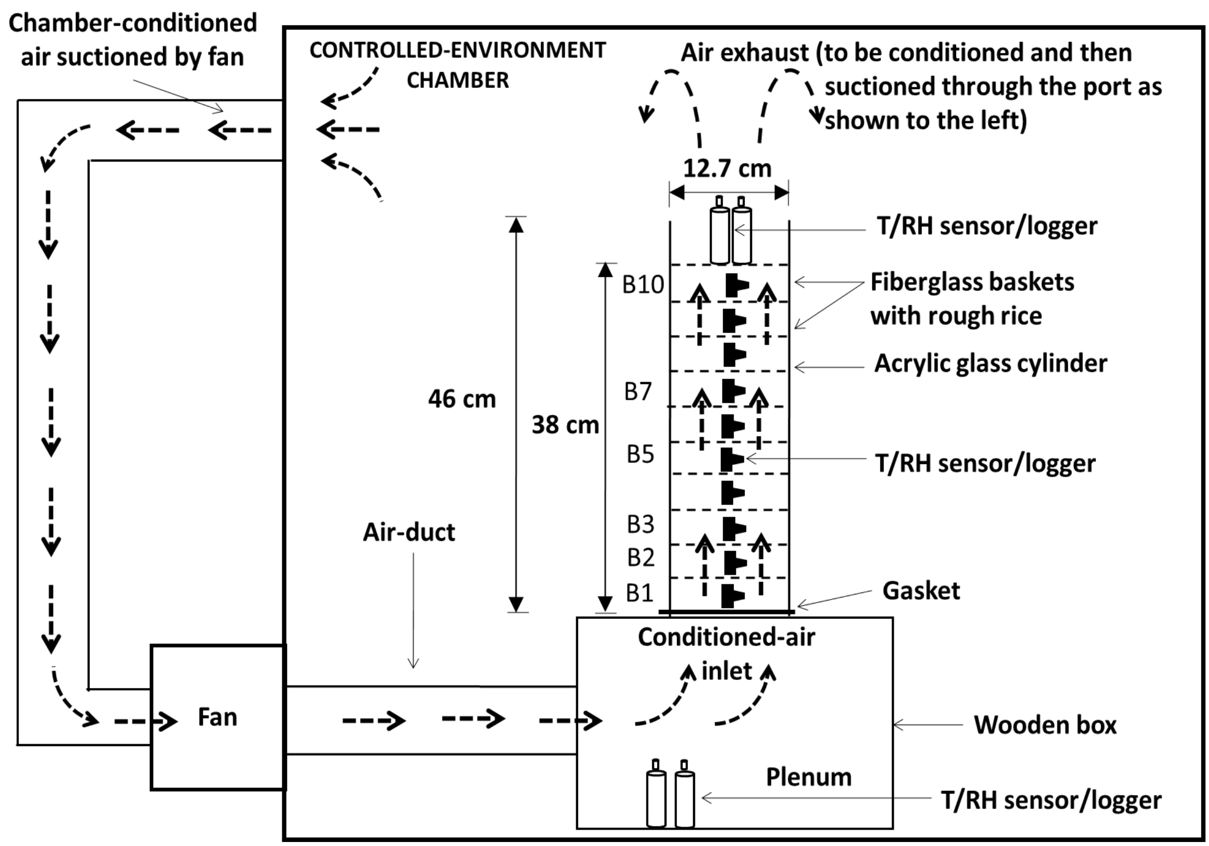

Fig. 1: Schematic diagram of the drying system. The drying assembly comprised a wooden box, an acrylic glass drying column with a metallic screen base, and a set of ten, fiber-mesh cylindrical baskets filled with rough rice and temperature/relative humidity (T/RH) sensors/loggers, all positioned inside a controlled-environment chamber.[17]

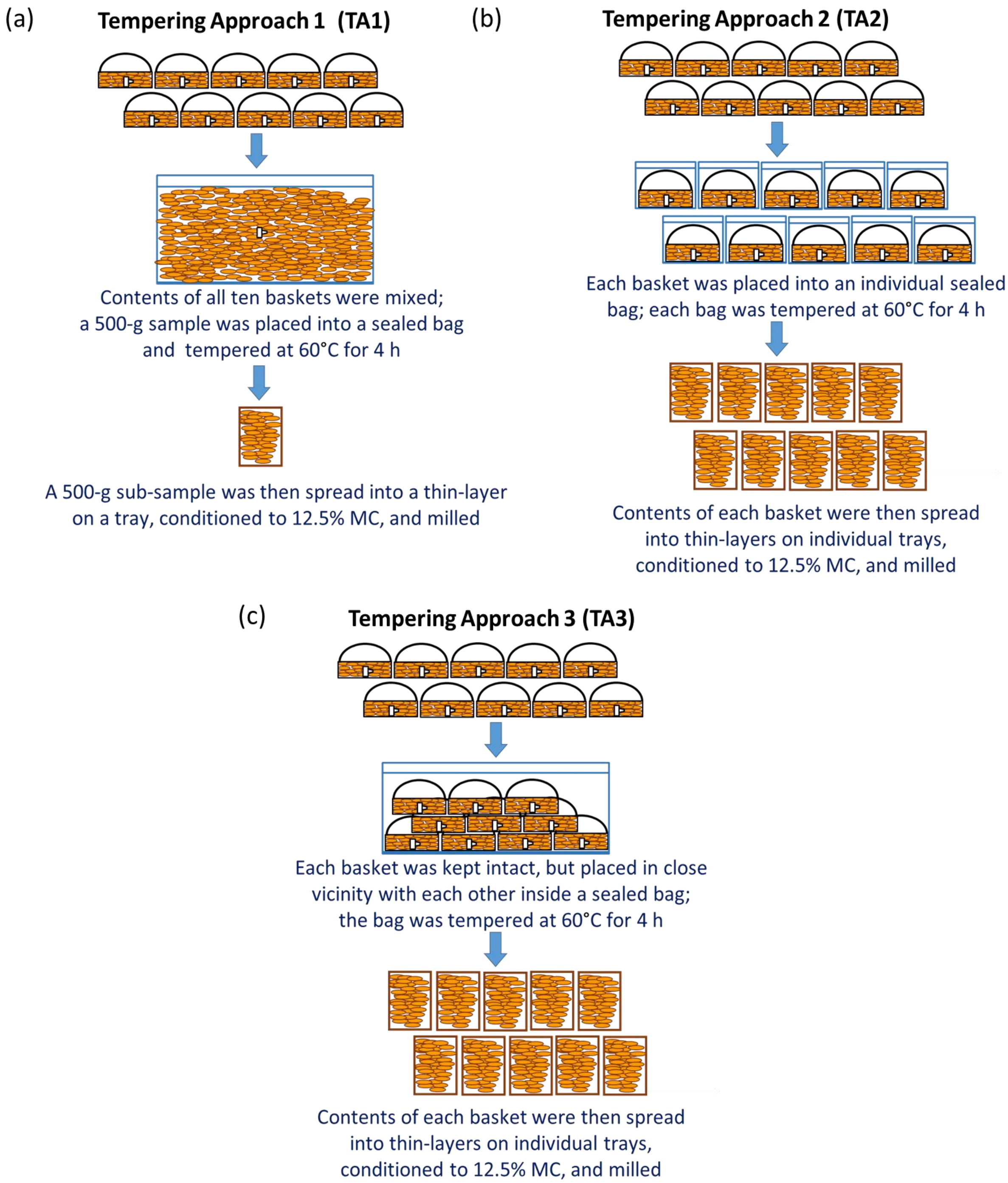

Fig. 2: Tempering approaches (TAs) TA1 (a), TA2 (b), and TA3 (c) followed after immediately prior-drying rough rice at 20.5% or 16.3% initial moisture contents in the drying assembly shown in Fig. 1 using 57°C/13% RH drying air at 0.56 $(m^3/s)/m^2$ for 30, 60 or 90 min.

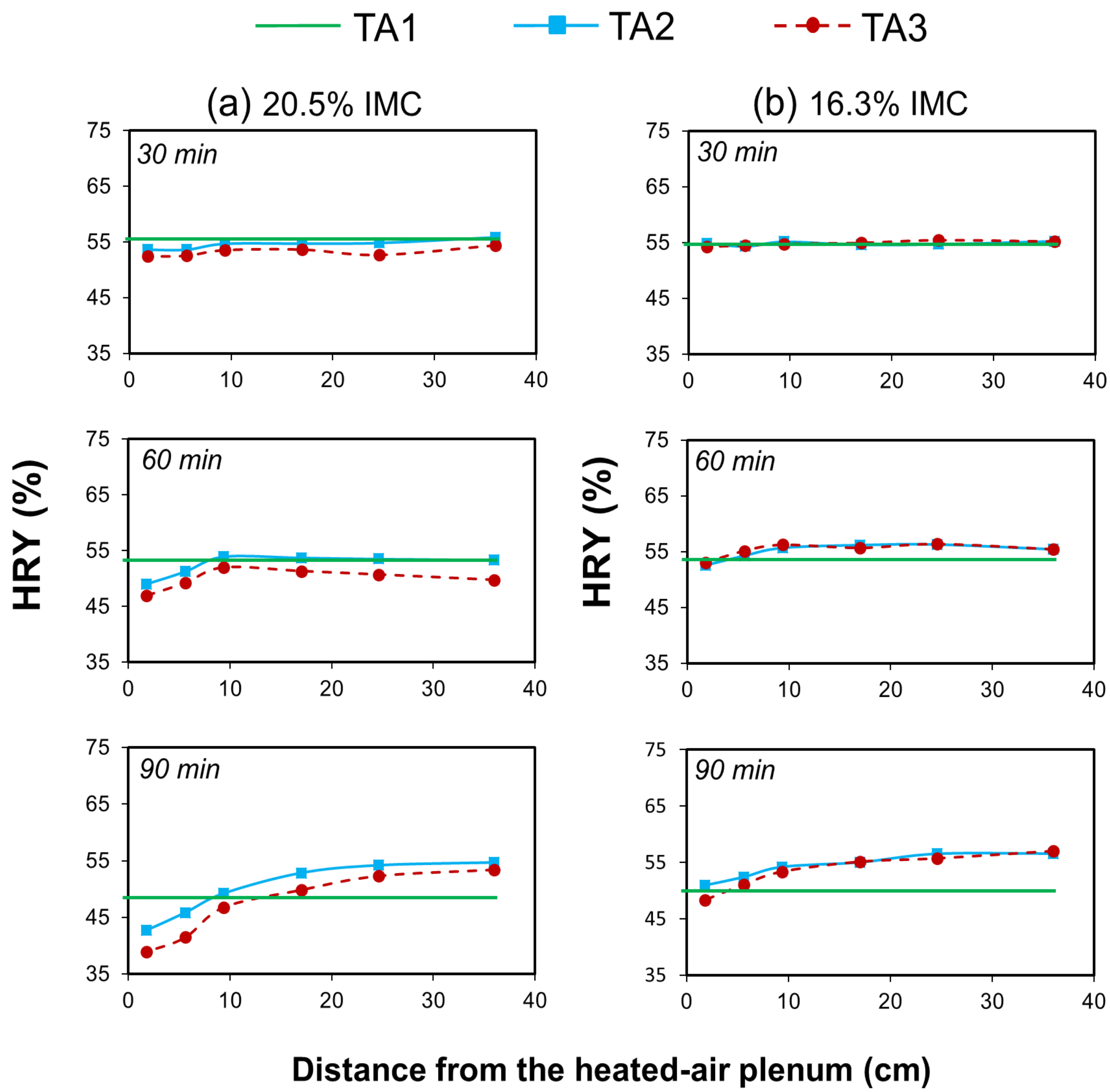

Fig. 3: Head rice yields (HRYs) after tempering immediately prior-dried rough rice lots at the 20.5% (a) and 16.3% (b) initial moisture contents (IMCs) using 57°C/13% RH drying air at 0.56 $(m^3/s)/m^2$ for 30, 60, and 90 min. The three tempering approaches shown above are detailed in Fig. 2; the line for TA1 represents the HRY of a composite sample of the entire drying column. Line/data points are the mean of two experimental treatment replications.

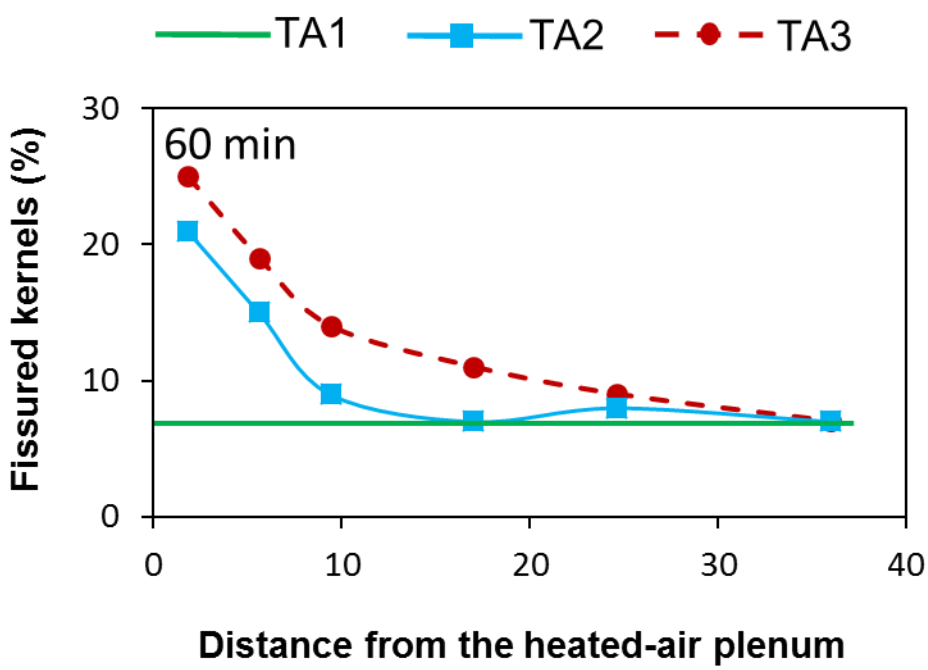

Fig. 4: Fissured kernels (%) after tempering immediately prior-dried rough rice at 20.5% initial moisture content using 57°C/13% RH drying air at 0.56 $(m^3/s)/m^2$ for 60 min. The three tempering approaches shown above are detailed in Fig. 2; the line for TA1 represents the fissured kernels (%) of a composite sample of the entire drying column. Line/data points are the mean of two experimental treatment replications.

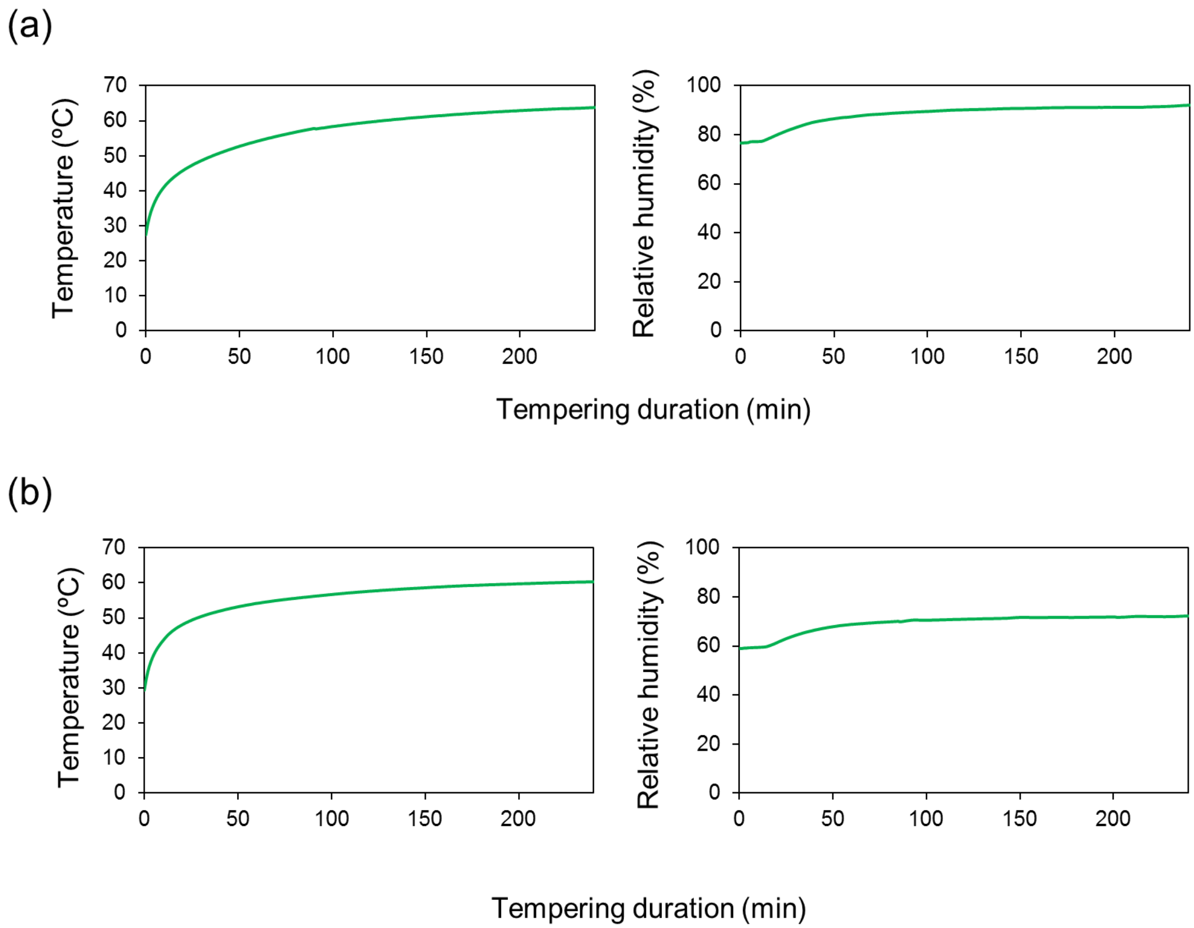

Fig. 5: Temperature and relative humidity profiles as a function of tempering duration when tempering approach 1 (TA1) was followed after immediately prior-drying rough rice at 20.5% (a) and 16.3% (b) initial moisture contents (IMCs) using 57°C/13% RH drying air at 0.56 $(m^3/s)/m^2$ for 60 min. Final MCs of the 20.5% and 16.3% IMC rice were 14.8% and 12.6%, respectively. TA1 is detailed in Fig. 2. Lines are the mean of two experimental treatment replications.

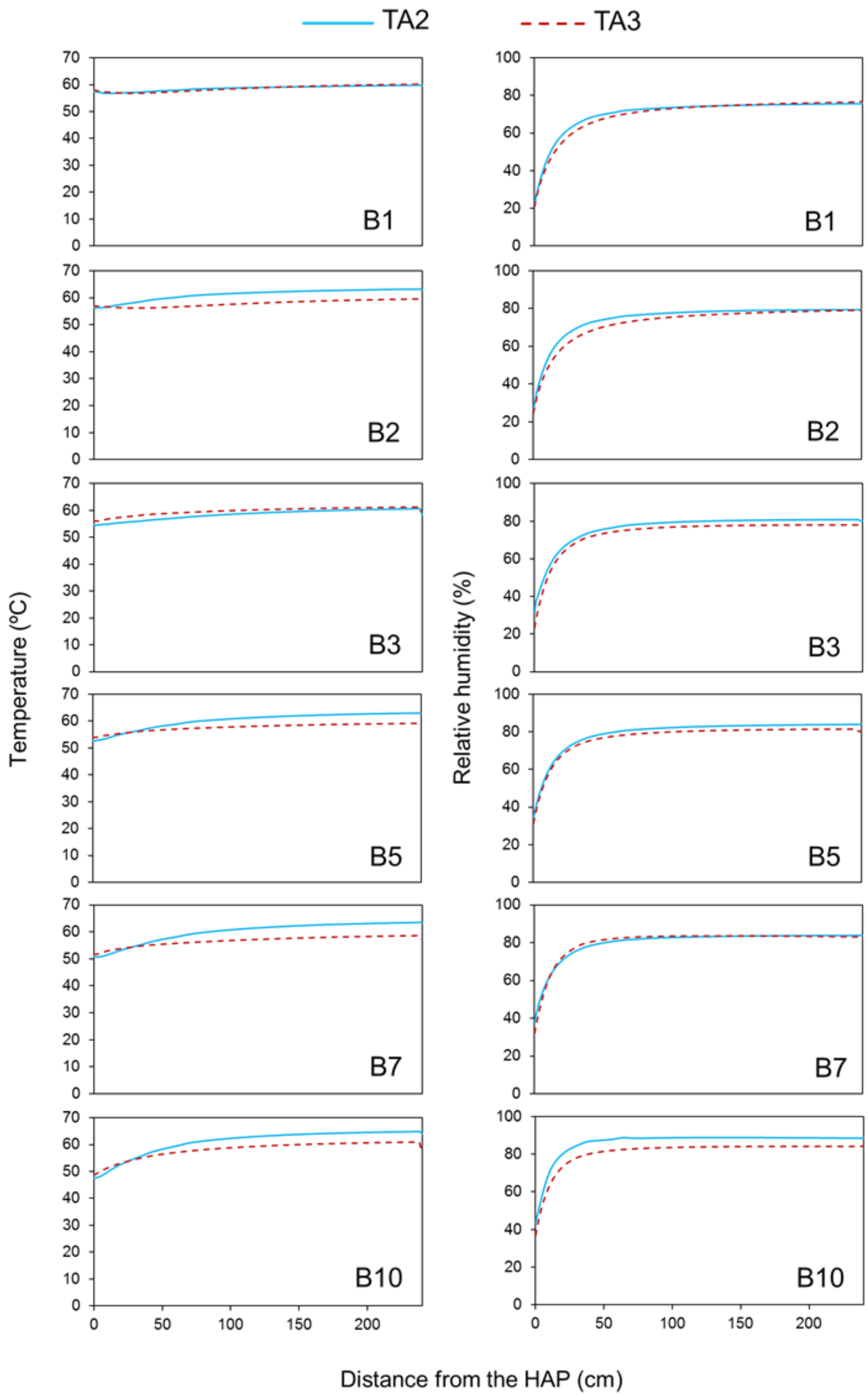

Fig. 6: Temperature and relative humidity profiles inside the indicated baskets as a function of tempering duration when tempering approaches TA2 and TA3 were followed after immediately prior-drying rough rice at 20.5% initial moisture content using 57°C/13% RH drying air at 0.56 $(m^3/s)/m^2$ for 60 min. During drying, basket 1 (B1) was nearest to the heated-air plenum. TAs are detailed in Fig. 2. Data points are the mean of two experimental treatment replications.

Table 1: Estimated asymptotic relative humidity (RH) and minimum tempering duration ($t_{0.95}$) for the indicated baskets when the indicated tempering approaches were followed after prior-drying rice at 20.5% initial moisture content (IMC) using 57°C/13% RH drying air at 0.56 (m^3/s)/m^2 for 60 min. Basket 1 (B1) was nearest to and B10 was farthest from the HAP as detailed in Fig. 1. Tempering approaches are detailed in Fig. 2. Estimates were obtained by fitting mechanistic growth models on the RH data.

Rough rice IMC (%)	Basket number	Tempering approach			
		TA2 (each basket was tempered separately)		TA3 (each basket was kept intact, but tempered together in one sealed bag)	
		Asymptotic RH (%)	$t_{0.95}$ (min)	Asymptotic RH (%)	$t_{0.95}$ (min)
20.5	B1	74.6	66	75.0	91
	B2	78.6	66	77.5	93
	B3	80.1	67	77.4	62
	B5	83.0	67	80.7	65
	B7	83.2	61	83.2	44
	B10	88.8	37	83.8	-
16.3	B1	60.7	89	68.3	103
	B2	63.4	62	71.7	94
	B3	67.5	74	69.5	81
	B5	69.5	72	71.7	77
	B7	72.0	45	72.6	57
	B10	79.3	47	80.3	-

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IV. CHAPTER 3

Glass Transition Effects on Milling Yields in a Cross-flow Drying Column

ABSTRACT

Drying treatments were selected based on the glass transition temperature of rice kernels and applied in an experimentally-simulated drying column. When kernels were dried in the glassy state, there was negligible head rice yield reduction (HRYR), regardless if samples had been tempered or not. But, when kernels transitioned to the rubbery state during the initial stages of drying and subsequently developed sufficient intra-kernel material state gradients, significant HRYRs occurred, and HRYRs of tempered samples were significantly less than those of non-tempered samples throughout the column. Sample HRYRs near the heated-air plenum were much greater than those into the column.

INTRODUCTION

Rice is typically harvested at 14% to 22% moisture content (MC) in the Mid-South United States of America (U.S.A). Unless otherwise specified, all MCs are reported on a wet basis. Soon after harvest, rice is dried to ~ 13% MC to minimize respiration rates and mold growth,[1] as well as to inhibit fungi and insect growth.[2] Since the amount of rice that must be dried per unit time is increasing owing to greater production, harvesting and transportation capabilities, there is a need to increase dryer throughput rates, while minimizing head rice yield reduction (HRYR). Head rice yield (HRY), the mass of head rice (milled kernels that are at least three-fourths of the original kernel length) expressed as a percentage of the original, dried rough rice mass,[3] is a direct determinant of the economic value of rice.

Commercial drying processes for rough rice typically comprise multiple drying passes, with periods of "tempering" between passes. Tempering allows intra-kernel moisture and material state gradients, which are typically created during drying, to subside.[4,5,6,7] This, in turn, improves the drying rate in subsequent drying passes,[8,9] thereby increasing overall energy efficiency.[10] Early research identified the importance of tempering in minimizing HRYR; tempering at elevated temperatures minimized fissuring,[11,12,13,14] maximized HRYs, [6,13,15,16,17,18,19,20,21] and decreased tempering durations.[13,19,22] In the U.S.A., tempering durations range between 6 and 24 h, and are generally based on the experience of dryer operators [22,23] and/or logistical harvesting/storage considerations.

The concept of glass transition in amorphous and semi-crystalline food matrices has been used to explain several phenomena, some of which include: spray drying and characteristics of spray-dried food products,[24,25,26] freeze drying of foods,[27,28] shrinkage and collapse in foods,[27,29,30] stickiness in foods,[31,32,33,34] porosity in foods,[35] and degradation kinetics of food constituents.[36] In the late 1990s and early 2000s, researchers found that the glass transition temperature (T_g) is an important parameter that influences many physical and mechanical properties that directly affect rice kernel fissuring and resultant breakage. The effect of MC on the T_g for individual brown rice kernels was studied using thermomechanical analysis; T_g increased linearly from 22ºC to 58ºC as MC decreased from 27% to 3%.[37] T_g was also measured using dynamic mechanical thermal analysis, deemed a more accurate and reliable method, especially at MCs < 15%.[38] Fig. 1 shows the T_g line and associated regression equation (Eqn. 1) developed by Siebenmorgen et al.[38]

$T_g = 100.5 - 334 \times \text{MC}, R^2 = 0.81$ (Eqn. 1)

where:

T_g is the glass transition temperature (ºC)

MC is the moisture content, expressed on a decimal wet basis

The material state of starch at a given location within a kernel is governed by both the starch MC and temperature.[37,39,40] This MC/temperature combination establishes the starch "position" relative to the T_g line on a material state diagram for rice and also determines the relative magnitude of many thermal, hygroscopic and mechanical kernel properties (Fig. 1).

A hypothesis based on intra-kernel material state behavior to explain fissure formation and subsequent HRYRs during the "drying process", which comprises drying and tempering, was recently introduced.[5] Drying rice kernels in the rubbery state is preferable to achieve greater drying rates, owing to the properties associated with the rubbery state, particularly greater moisture diffusivity (Fig. 1). During the initial stages of heated-air drying, both intra-kernel temperature and MC gradients form (inset in Fig. 2). However, unlike MC gradients, temperature gradients within a kernel subside within the first 2 to 3 min of drying.[41,42] With extended drying, a sufficient volume of the kernel periphery will transition from the rubbery state to the glassy state, due to its decreased MC (Fig. 2). The T_g hypothesis states that during drying, if a sufficient volume of the kernel periphery transitions into the glassy state, while the center is still in the rubbery state, fissures can initiate because of the vastly different physical and mechanical properties of these volumes.[19]

Additionally, material state behavior was used to address the occurrence of fissures after drying ceases, particularly during tempering.[5] Even if the intra-kernel material state gradients developed are not sufficient to cause fissuring during drying, a kernel could still fissure during tempering, depending on the tempering temperature. If the tempering temperature is such that the peripheral volumes of the kernel are forced to transition to the glassy state due to rapid cooling of the kernel surface, while its center remains in the rubbery state, the resultant intra-kernel material state gradients are hypothesized to cause fissures; this is shown with situation (a) in Fig. 3. However, if the tempering temperature is such that the kernel is held in the rubbery state for a sufficient duration such that its internal MC and material state gradients subside to an appreciable degree, the kernel will not fissure if it is subsequently cooled, as shown with situation (b) in Fig. 3.

Several studies have been conducted to observe fissure formation and consequent HRYR during the rice drying process to validate the T_g hypothesis.[5,19,43] All these studies comprised "thin-layer", stationery-bed drying tests with the layers generally being ~ 0.6 cm in thickness. However, in actual cross-flow dryers, rice is dried in column thicknesses ranging between 30 and 45 cm. Since drying air conditions (temperature and relative humidity) change as the air travels through this "thick-layer", rice kernels experience different drying conditions depending on their distance from the heated-air plenum (HAP).[44]

The present study was conducted with the goals of quantifying milling yield patterns within an experimentally-simulated, cross-flow drying column and determining if intra-kernel material state behavior could be used to explain the milling yield patterns. The objectives were to: (1) quantify the effects of drying and tempering treatments on moisture contents (MCs) and milling yields as a function of location within the column, and (2) study the effects of intra-kernel material state gradients on milling yields within the column.

MATERIALS AND METHODS

Overview of the experiment. The experimental design consisted of drying/tempering treatments, with drying air temperatures selected to induce different extents of material state gradients in rice kernels. Drying runs were conducted in a specially-designed apparatus that allowed measurement of MC and HRY throughout a drying column. Four drying air temperature/relative humidity (T/RH) combinations were combined with four tempering approaches; each drying/tempering treatment was replicated twice, thus yielding 32 drying/tempering runs.

Sample procurement and preparation. A 300-kg bulk lot of rough rice (long-grain cultivar Roy J) was combine-harvested at the University of Arkansas Rice Research & Extension Center, Stuttgart, AR in September, 2015 at 23.2% MC. The lot was cleaned using a dockage tester (XT4, Carter-Day, Minneapolis, MN, U.S.A.) to remove foreign material and unfilled kernels. Then, a 150-kg sub-lot was gently conditioned to approximately 16% MC using air at 26°C/56% RH, and stored in sealed containers at 4°C for 4 months. Immediately prior to drying treatments, the rice MC was determined to be 16.3% by drying duplicate, 15-g sub-samples in a convection oven (1370FM, Sheldon Manufacturing Inc., Cornelius, OR, U.S.A.) maintained at 130°C for 24 h.[45]

Experimental system. Drying runs were accomplished inside a 0.91-m^3, controlled-environment chamber (Platinous Sterling Series, ESPEC North America, Hudsonville, MI, U.S.A.) that was capable of producing drying air at the required T/RH combinations. During operation, a centrifugal fan (4C108, Dayton Electric Manufacturing Co., Niles, IL, U.S.A.), coupled to a 0.56-kW electric motor (3N443BA, Dayton Electric Manufacturing Co., Niles, IL, U.S.A.) suctioned air at the desired T/RH from the chamber through a port located in the front door of the chamber, and then forced the air through a side-wall port in the chamber wall to a drying assembly (Fig. 4). A variable-frequency drive (AF-300 Mini, GE Fuji Drives USA Inc., Salem, VA, U.S.A.) was connected to the fan motor to achieve the desired airflow rate of 0.56 $(m^3/s)/m^2$.

The drying assembly comprised a wooden box that served as a HAP, an acrylic glass drying column with a metallic screen base, and a set of ten, fiber-mesh, hand-woven cylindrical baskets (3.8-cm thick, 12.7-cm diameter). The fiber-mesh baskets were used as “sample holders” for the rough rice and enabled the drying column to be divided into discrete layers, thus permitting sampling at various distances from the HAP. Each basket had a fiber-mesh flap on top that could be fastened using metal pins, and a fiber-mesh handle to facilitate dismantling after the completion of a drying run.

Drying air conditions. Drying air T/RH combinations were selected to either dry rice kernels entirely in the glassy state or to induce different extents of material state gradients in the kernels. According to Eqn. 1, the T_g of a brown rice kernel at 16.3% MC is 46°C. Thus, a condition of 40°C/32% RH, with a corresponding rough rice equilibrium MC (EMC) of 8.0% (Modified Chung-Post equation)[46], was selected to maintain rice kernels in the glassy state. From the T_g hypothesis standpoint, no HRYR was expected, even after an extended period of drying in the glassy state, using this drying treatment. Conditions of 50°C/18% RH, 60°C/12% RH, and 70°C/8% RH, with corresponding rough rice EMCs of 5.4%, 3.7%, and 2.2%, were used to induce intra-kernel material state gradients in the rice kernels. Drying for an extended period under these air conditions would cause different extents of the kernel periphery to transition from the rubbery state to the glassy state (due to reduced MCs of the kernel periphery) while the center remained in the rubbery state; this would hypothetically lead to the development of fissures and consequent HRYR. All T/RH combinations were selected to have the same humidity ratio of 0.015 kg water/kg dry air and a drying duration of 60 min was used.

Drying procedure. Approximately 2.7 kg of rough rice was removed from cold storage, placed in a sealed bag and equilibrated to room temperature (22°C) for 24 h prior to each drying run. Each of the ten baskets was filled with 270 g of rough rice and a T/RH sensor/logger (UX100-011, Onset Corporation, Bourne, MA, U.S.A.) to measure air conditions every 60 s during drying. Stacking the ten baskets in the acrylic glass cylinder resulted in a 38-cm thick rice column. Additional T/RH sensors were placed inside the HAP and at the top of the rice column to record air conditions at the column inlet and exhaust, respectively. When the controlled-environment chamber stabilized at the T/RH setting for a drying run, the chamber door was opened for < 1 minute to position the rice column on the HAP. After the 60-min drying duration, the drying column was dismantled.

Tempering approaches and procedures. In commercial cross-flow dryers, rice flows downward through the drying columns and feed-roll augers meter the dried rice out of the columns. Thus, the rice from a column cross-section is mixed as it exits the dryer. In order to simulate this experimentally, two of the four tempering approaches (Table 1) comprised mixing of the rice from all ten baskets immediately after drying. However, because it was also desired to quantify milling yield trends as a function of distance from the HAP, the other two tempering approaches comprised preserving the rice from each basket as separate samples during tempering.

The effect of tempering on milling yield was studied by incorporating "non-tempered" and "tempered" scenarios. The tempering approaches (Table 1) simulated the two situations described in Fig. 3; the first comprised rapid cooling, thereby making extended portions of kernel peripheries to immediately undergo a state transition and the second comprised "holding" the kernels at temperatures that would allow intra-kernel material states to subside. In the tempered scenarios, a 4-h tempering duration, deemed sufficient for significant subsidence of intra-kernel material state gradients[6,7,43] was used. All the tempering procedures were conducted immediately (< 1.5 min) after drying ceased and are detailed in Table 1.

At the end of each drying run, in addition to the samples taken for tempering, a 40-g sample was taken after mixing the contents of all the baskets, allowed to equilibrate in a sealed plastic bag at 22°C for 48 h, and MC measured following the above oven-drying procedure to indicate the final average MC of the column. A 40-g sample was also taken from each basket for MC analysis to indicate the final MC as a function of distance from the HAP. The T/RH sensors were retrieved after each drying run and the data downloaded.

Milling analyses. Each of the tempering approaches in which rice from all the baskets was mixed yielded one milling sample per drying/tempering treatment while each of the tempering approaches in which baskets were kept separate yielded ten milling samples. However, for the individual baskets, it was reasoned that the milling yields of baskets B1, B2, B3, B5, B7, and B10 (Fig. 4) would provide sufficient trends across the rice column. Hence, for each drying air combination, 14 samples were produced (2 from the 2 bulk-column tempering approaches + 12 from the 2 individual-basket tempering approaches). With a total of 4 T/RH combinations and 2 replications, 112 samples were milled.

For each milling analysis, a 150-g rough rice sample was dehulled using a laboratory huller with a clearance of 0.048 cm between the rollers (THU-35A, Satake Engineering Co., Ltd., Tokyo, Japan). The brown rice was then milled for 19 s (previously determined as the milling duration required to achieve 0.4% surface lipid content) using a laboratory mill (McGill No. 2, Rapsco, Brookshire, TX, U.S.A.) with a 1.5-kg mass placed on the lever arm 15 cm from the center of the milling chamber. A sizing device (61, Grain Machinery Manufacturing Co., Miami, FL, U.S.A.) was then used to separate head rice from brokens. Milling yield was quantified by the milled rice yield (MRY) and HRY; MRY represents the mass of milled rice, and HRY the mass of head rice, both expressed as a percentage of the original, 150-g rough rice mass.

Controls. Control milling yields were produced by removing 2 kg of rough rice from the stored, bulk lot and conditioning to 12% MC using air at 26°C/56% RH. Preliminary experiments were conducted to show that extended drying at 26°C/56% RH did not produce any reductions in milling yield. Five, 150-g samples were milled per the procedure described above and the yields averaged.

Statistical analyses. Analysis of variance (ANOVA, $\alpha = 0.05$) was conducted and means separated using the Fishers Least Significant Difference procedure (LSD, $P < 0.05$) using JMP Pro software (Version 12.0.1, SAS Institute, Inc., Cary, NC, U.S.A.).

RESULTS AND DISCUSSION

Drying air conditions and final moisture contents. The actual drying air conditions at the HAP were 40ºC/26% RH, 50ºC/17% RH, 57ºC/13% RH, and 64ºC/9% RH, corresponding to the desired conditions of 40ºC/32% RH, 50ºC/18% RH, 60ºC/12% RH, and 70ºC/8% RH (Table 2). At temperatures above 50ºC, the actual temperature values were less than desired, likely due to heat loss through the connecting duct located outside the chamber (Fig. 4). Table 2 also provides the final bulk-column MCs for each drying air condition after 60 min of drying.

Non-uniformity of MCs within the drying column is evident from Fig. 5; for all drying air conditions, final MCs consistently increased with distance from the HAP. These trends were expected per psychrometric relations as the drying air had maximum drying capacity at the HAP, but as it passed through the rice column, following a path of adiabatic saturation, its drying capacity progressively decreased as moisture was evaporated from the rice. However, for all drying conditions, considerable drying occurred near the exhaust.

Fig. 5 also shows the expected trends that, like the bulk-column MC trends of Table 2, final MCs of the individual baskets decreased with increasing severity of the drying air condition. Additionally, the final MC range within the drying column increased dramatically when drying with the more severe drying air conditions. For example, the MC range within the column increased from 1.3 percentage points (PPs) (13.6% at B1 to 14.9% at B10) for the 40ºC/26% RH drying air condition to 1.6 PPs (12.5% at B1 to 14.1% at B10) for the 50ºC/17% RH condition. But this MC range increased to 2.6 PPs (11.5% at B1 to 13.6% at B10) and 2.5 PPs (10.1% at B1 to 12.5% at B10) for 57ºC/13% RH and 64ºC/9% RH drying air conditions, respectively.

Moreover, as severity of the drying air condition increased, rice near the HAP was increasingly over-dried, i.e., past the typical 12.5%-MC level (Fig. 5). For example, when using 57ºC/13% RH drying air, although the bulk-column MC was 12.6% (Table 2), B1 reached a final MC of 11.5% (Fig. 5). Similarly, when using 64ºC/9% RH drying air, the bulk-column MC was 11.5%, but B1 reached a final MC of 10.1%; since the thickness of each basket was 3.8 cm, it is likely that the rice kernels immediately adjacent to the HAP were severely over-dried to MCs of 5% to 6%.

Milling yields of the bulk column. The MRYs and HRYs of the bulk column are shown in Fig. 6. MRYs were similar across drying air conditions and similar to the control, except for the most severe drying air condition (64ºC/9% RH), wherein MRY decreased from the control and the corresponding MRYs at the less severe drying air conditions. It is speculated that at this drying air condition, sufficient kernel fissuring resulted in the generation of small kernel fragments that left with the bran stream during milling, thereby decreasing the overall MRY. Fig. 6A also shows that for each drying air condition, MRY was not affected by whether or not the rice was tempered after drying.

Unlike MRYs, HRYs of treatment samples were similar to the control only under the mild drying air conditions but then decreased progressively with increasing drying air severity; this will be expounded upon later. Additionally, for the 40ºC/26% RH and 50ºC/17% RH drying air conditions, there was no significant difference between HRYs of tempered and non-tempered samples (Fig. 6B). However, tempering consistently produced greater HRYs compared to no tempering for the 57ºC/13% RH and 64ºC/9% RH drying air conditions.

Milling yields within the column. The bulk milling yield trends (Fig. 6) were explained by the variation in milling yield throughout the individual baskets that constituted the 38-cm thick bulk column (Fig. 7). As expected from Fig. 6A, overall MRY trends were similar across the baskets for all drying conditions. The decrease in the bulk-column MRY when using 64ºC/9% RH drying air occurred due to the cumulative effect of the decrease in MRYs of the first few baskets near the HAP, respectively, although this is not clearly evident from Fig. 7A owing to the scale used in the plot. Expectedly, there was no significant difference between the MRYs of the tempered and non-tempered samples of the individual baskets.

Fig. 7B shows the accompanying HRYs throughout the drying column. When drying with the two less severe air conditions, HRYs of all the baskets were not significantly different from the control. Additionally, there was no statistical difference between tempered and non-tempered HRYs of the individual baskets when using these two less severe conditions, although the tempered-sample HRYs tended greater than the corresponding non-tempered HRYs.

However, when drying with the two more severe air conditions, HRYs were progressively less near the HAP than those into the column. Additionally, the overall HRY values decreased significantly from the control with increasing severity of the drying air condition. Tempering of samples produced HRYs significantly greater than non-tempered HRYs, especially in the baskets near the HAP; the difference between HRYs of tempered and non-tempered samples progressively decreased with distance from the HAP. For example, for the 57ºC/13% RH drying condition, B1-, B2-, and B3-HRYs after tempering were 15.3, 12.7, and 8.8 PPs greater than the corresponding non-tempered samples. But, B5- and B7-HRYs after tempering were only 3.6 and 0.8 PPs greater than the corresponding non-tempered HRYs.

The HRY trends due to drying air condition, sample location within the column, and tempering treatment after drying are inter-related and are addressed in light of T_g and material state gradients. For this, a hypothetical "drying trajectory" of the bulk rice in each basket was plotted on the state diagram for rice[38] to pictorially estimate the "position" of the rice kernel bulk during drying. In this visualization, two considerations are relevant.

The first is that although the average MC and grain temperature of the bulk rice in the baskets are used to establish the "position" on the state diagram before and after drying, in reality, there is a tremendous range in MCs of individual rice kernels that constitute the bulk. To illustrate this point, MCs of 200 kernels were measured (five replications) using a single kernel moisture meter (Shizuoka Seiki CTR 800E, Shizuoka, Japan). The range of individual-kernel MCs for rice at 16.3% initial MC (IMC) was between 13.5% and 18.5% (Fig. 8). As such, each kernel comprising the bulk would have a different drying trajectory, with possibly different state transitions during the process. This is illustrated in Fig. 9, in which initial and final kernel state points and the hypothetical drying trajectories of three individual rice kernels of different MCs are shown along with the bulk-grain state points and the corresponding drying trajectory of the bulk rice in B1. Fig. 9 shows that the low-MC kernels in the population would be expected to have different initial and final state points, as well as different drying trajectories, than the medium-MC kernels and high-MC kernels in the population. Correspondingly, these kernels would be expected to have different intra-kernel material state gradients, depending on the drying air condition. The individual-kernel MC frequency distribution may explain why some kernels fissure during a drying process while others do not. Hence, HRYR trends ought to be considered in light of individual-kernel behavior relative to the T_g line.

A further level of complexity relevant to explaining HRYRs is that the "T_g line" is, in reality, a band of temperatures. An R^2-value of 0.81 was indicated for the regression equation relating rice T_g with MC.[38] As such, the "boundary" between glassy and rubbery regions is not as well-defined as is depicted in Fig. 1.

Intra-kernel material state gradients. Fig. 10 shows the bulk average MCs and grain temperatures of selected baskets, as well as that of the control samples before and after drying. For each drying air condition, the IMC (16.3%) and initial grain temperature (20.5°C) were plotted on the state diagram, as were the bulk MCs and grain temperatures of the rice in B1, B3, B5, B7, and B10 at the end of the 60-min drying duration. Hence, B1, being nearest to the HAP, had the least final MC and the maximum grain temperature. A hypothesized trajectory of the rice in B1 and B10 during drying is also shown. Finally, the MC and corresponding HRY reductions of the tempered rice from individual baskets are inset for each drying air condition.

Although the points showing the bulk MC and temperature (T) (Fig. 10) give the average conditions of kernels in the respective baskets, fissuring and resultant HRYR during the drying process is actually dependent upon the extent of intra-kernel material state gradients formed inside the kernels, which in turn, is dependent on the drying air condition. At a given drying air condition, the surface of the kernel attains equilibrium with the drying air soon after drying commences, but the interior volumes of the kernel do not, this creates intra-kernel MC and material state gradients within the kernel. The greater the severity of the drying air condition, with correspondingly lesser associated rough rice EMC, the greater the extent of intra-kernel material state gradients formed inside the kernels. For example, when using 50°C/17% RH drying air (rough rice EMC = 5.2%), the intra-kernel MC gradient for any given kernel would be the difference between the IMC of the individual kernel at its center and 5.2% MC at the kernel surface. Thus, intra-kernel MC gradients would vary considerably from kernel to kernel depending on the IMC of the kernel within the bulk, as illustrated in Fig. 8. When using 64°C/9% RH air (rough rice EMC = 2.8%), the intra-kernel MC gradients would correspondingly increase as now the kernel surface would be expected to equilibrate rapidly to 2.8% rather than 5.2%. Thus, these different intra-kernel MC gradients would result in different material state gradients inside each kernel.

The control samples, which were dried using 26°C/56% RH drying air, had the maximum HRYs among all samples (Fig. 7), and overall HRYs decreased progressively from the control value as treatment drying conditions became more severe. These results concurred with previous studies,[20,22] wherein the use of a gentle drying condition, like that of the control, consistently resulted in greater HRYs than those obtained when heated-air was used, even if drying was followed by elevated-temperature tempering. These steadily decreasing HRY trends compared to the control can be explained by plotting the drying trajectory of the control in Fig. 10. As explained above, during drying at the 26°C/56%RH condition (rough rice EMC = 12.0%), the intra-kernel MC gradients were much less than those when using more severe drying conditions that had lesser EMCs; all the kernels in the 16.3%-IMC sub-lot were maintained entirely in the glassy state, therefore, no kernels transitioned into the rubbery region, thus, fissuring and resultant HRYR did not occur.

When 40ºC/26% RH drying air was used, practically all the kernels in the 16.3%-IMC rice remained in the glassy state during drying, hence, few, if any, fissured during drying, and there was minimal HRYR. It is speculated that the minimal HRYR that occurred at this condition was from the high-MC kernels that transitioned into the rubbery region. On increasing the drying air condition severity to 50ºC/17% RH, the drying trajectories, particularly those for high-MC kernels, suggest slight transitions into the rubbery region (Fig. 10), but not severe enough for significant HRYR. Further increase of the severity of the drying air condition caused more kernels to transition into the rubbery region; as drying progressed, the peripheries of many kernels transitioned back to the glassy state, leading to intra-kernel material state gradients and possible fissuring. Moreover, it would be expected that an increasing number of kernels would fissure as drying air severity increased as the EMC of the drying air would decrease, thereby creating increasingly greater intra-kernel material state gradients. Thus, with increasing severity of the drying air condition, HRYRs increased, and the effect was more prominent in the baskets near the HAP.

Fig. 10 can also be used to explain the effect of tempering on HRYR. After 16.3%-IMC rice was primarily dried in the glassy state using 40ºC/26% RH drying air, exposing this rice to 26ºC did not initiate any state transition because most kernels remained in the glassy region during drying. As a result, fissuring and consequent HRYR did not occur. When 50ºC/17% RH drying air was used, HRYs of the tempered samples tended greater than those of the samples that were not tempered because even the high-MC kernels that underwent a state transition to the rubbery region had sufficient time during tempering for subsidence of material state gradients prior to cooling and therefore, did not fissure, and thus, minimize HRYR. When drying air conditions became more severe (57ºC/13% RH and 64ºC/9% RH), progressively greater intra-kernel moisture gradients were created during drying, such that at the most severe drying condition of 64ºC/9% RH, the HRY of the basket next to the HAP, even after tempering (40.7%) was very low compared to the corresponding HRY values when less severe drying air conditions were used. In such severe drying, it is postulated that the intra-kernel material state gradients were sufficient to cause many kernels to undergo severe structural fissuring during drying. In such cases, tempering at an elevated temperature could not restore HRYs to the values obtained when less severe drying conditions were used but tempering significantly helped in recovering HRY to a large extent by allowing the subsidence of these material state gradients in many kernels before cooling occurred.

The HRY trends of Fig. 7 for tempered and non-tempered samples concur with validation testing[5,19,44] of the T_g hypothesis in that tempering at an elevated temperature minimized HRYRs whenever drying air conditions were such that kernels transitioned into the rubbery state during the initial stages of drying and developed sufficient intra-kernel MC gradients. Having established the need for tempering using elevated temperatures so as to maintain kernels in the rubbery state before subsequent cooling, the subsequent discussion will be limited to samples that were tempered at the drying air temperature for 4 h.

The insets in Fig. 10 show that for the same moisture content reduction (MCR), HRYR differed across drying air conditions, suggesting that HRYRs depended on the extent of material state gradients created within the kernels and not merely on the intra-kernel MC gradients. For example, when 40ºC/26% RH drying air was used, B1 had a MCR of 2.7 PPs and a corresponding HRYR of 2.7 PPs but when 57ºC/13% RH drying air was used, B10 had the same MCR but a much greater HRYR of 5.5 PPs. Similarly, when 50ºC/17% RH drying air was used, B1 had a MCR of 3.8 PPs and a corresponding HRYR of 1.9 PPs, but when 57ºC/13% RH drying air was used, B5 had a greater HRYR of 3.7 PPs for the same MCR, and when 64ºC/9% RH drying air was used, B10 had an even greater HRYR of 6.9 PPs when 3.8PPs of MCR occurred.

Initial moisture content and drying duration. It was desired to study the impact of IMC on intra-kernel material state gradients and resultant HRYR in thick-column applications, thus additional drying runs were conducted using rice at a greater IMC than that used in the main study. Following the procedure described above, a 20-kg sub-lot was removed from the stored bulk lot and gently conditioned to ~ 21% MC (actual IMC = 20.5%). For simplicity, a single, typical cross-flow drying air condition of 57ºC/13% RH was used with the same airflow rate of 0.56 $(m^3/s)/m^2$; however, three drying durations (30, 60, or 90 min) were selected to produce a range of MC reductions. Having established the importance of elevated-temperature tempering earlier, following a drying run, only the two "tempered" approaches listed in Table 1 were conducted. Each drying/tempering treatment was replicated twice, hence, 6 additional drying runs (3 drying durations X 2 replications) were conducted, which resulted in 42 milling samples (6 drying runs X (1 milling sample from the bulk column + 6 milling samples from individual baskets)).

The 57ºC/13% RH drying condition-plot in Fig. 10 and the 60 min-plot in Fig. 11 show that all other drying conditions being same, more drying occurred when rice at a greater IMC, viz. 20.5%, was used, as quantified by the MCRs in the insets of each figure. For example, the MCR in B1 containing 16.3%-IMC rice was 4.8 PPs (Fig. 10; 57ºC/13% RH-plot), but the MCR in B1 containing 20.5%-IMC sub-lot was 7.8 PPs (Fig. 11; 60-min plot). Additionally, when using 57ºC/13% RH drying air, the HRYR in B1 containing 16.3%-IMC sub-lot was 5.1 PPs (Fig. 10; 57ºC/13% RH-plot) but the HRYR in B1 containing 20.5%-IMC sub-lot was 12.6 PPs (Fig. 11; 60-min plot). The greater HRYRs in the 20.5%-IMC sub-lot compared to those in the 16.3%-IMC sub-lot is postulated to be due to greater material state gradients being created inside the kernels constituting the 20.5%-IMC sub-lot than those inside the kernels constituting the 16.3%-IMC sub-lot.

Fig. 11 also shows that as drying duration increased, HRYRs of the individual baskets increased, and these effects were more prominent in the baskets near the HAP. For example, after a 30-min drying duration, MCR ranged from 5.8 PPs at B1 to 2.0 PPs at B10 and corresponding HRYR ranged from 7.3 PPs at B1 to 5.1 PPs at B10. As the drying duration increased to 60 min, MCR ranged from 7.8 PPs at B1 to 4.2 PPs at B10 and corresponding HRYR ranged from 12.6 PPs at B1 to 7.0 PPs at B10. With further drying for 90 min, MCR ranged from 9.5 PPs at B1 to 6.5 PPs at B10 and corresponding HRYR ranged from18.2 PPs at B1 to 6.3 PPs at B1. These results concurred with previous findings[38] and suggested that with increasing drying duration, progressively larger portions of the kernel periphery transitioned into the glassy region while the center remained in the rubbery region, a condition that led to intra-kernel stress differentials that exceeded material strength, and thus, resulted in structural failure and fissuring.

Additionally, when drying a 38-cm thick column of rice using 57ºC/13% RH air at an airflow rate of 0.56 $(m^3/s)/m^2$ for 60 min, the final bulk column MCs for the 16.3%- and the 20.5%-IMC sub-lots were 12.6% (Table 2) and 15.2%, respectively, which represented a MCR of 3.7 PPs and 5.3 PPs, respectively. The bulk-column HRY for the 16.3%-IMC sub-lot (57.7%)

was significantly greater than that for the 20.5%-IMC sub-lot (53.2%). Hence, for the same drying air condition, the MCR that could be achieved in a single pass without incurring essentially any HRYR (Fig. 6) was dependent on the IMC of the rice lot, i.e., 16.3%-IMC rice could be dried to 12.6% MC in a single pass without incurring HRYR, provided sufficient elevated-temperature tempering occurred immediately after drying, but this was not possible if the rice was at 20.5% IMC.

CONCLUSIONS

The experimental set-up and approach of this study provide unique MC and milling yield profiles throughout a typical cross-flow drying column as a function of drying air condition. These values provide data that can be used for validation of mathematical models predicting MC and milling yield profiles in such dryers, and thus, will contribute towards improved dryer design. The HRY trends for tempered and non-tempered samples from the drying column concur with validation test results obtained in thin-layer drying studies[5,6,19,43], pertaining to the T_g hypothesis, thus suggesting that the intra-kernel material state gradients can be used to explain the occurrence of fissures and resultant HRYRs in cross-flow drying scenarios.

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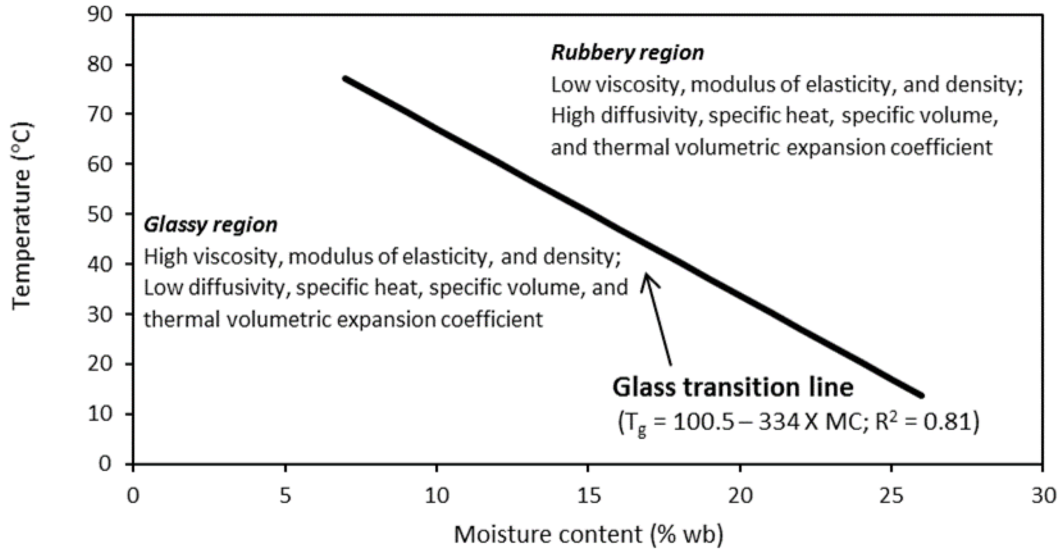

Fig. 1: Glass transition temperature (Tg) as a function of moisture content (MC) for brown rice kernels, indicating the "glassy" and "rubbery" regions, as well as the properties associated with each region.[38]

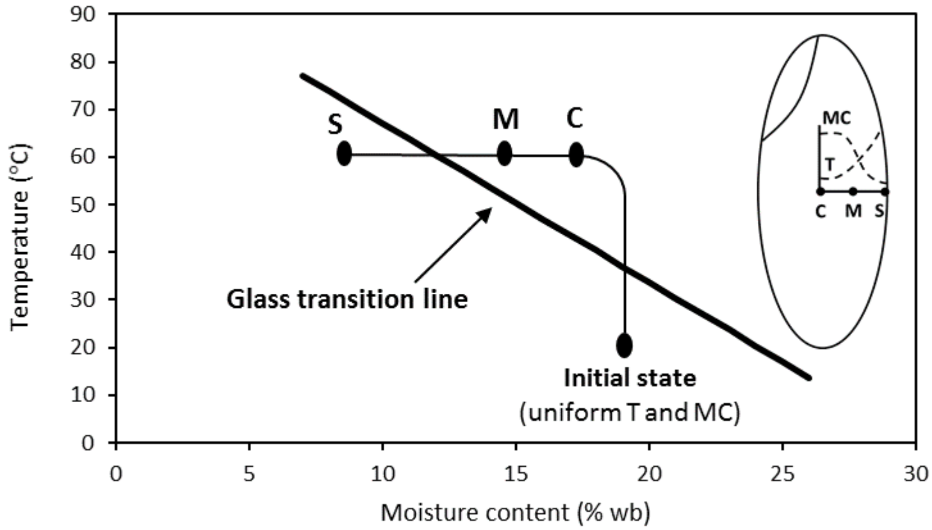

Fig. 2: Hypothetical temperature (T) and moisture content (MC) gradients within a brown rice kernel at locations shown in the inset[5] after extended high-temperature drying, superimposed on the glass transition line from a previous study.[38] Points C, M, and S on the x-axis of the plot correspond to the center, mid-point, and surface of the rice kernel, respectively.

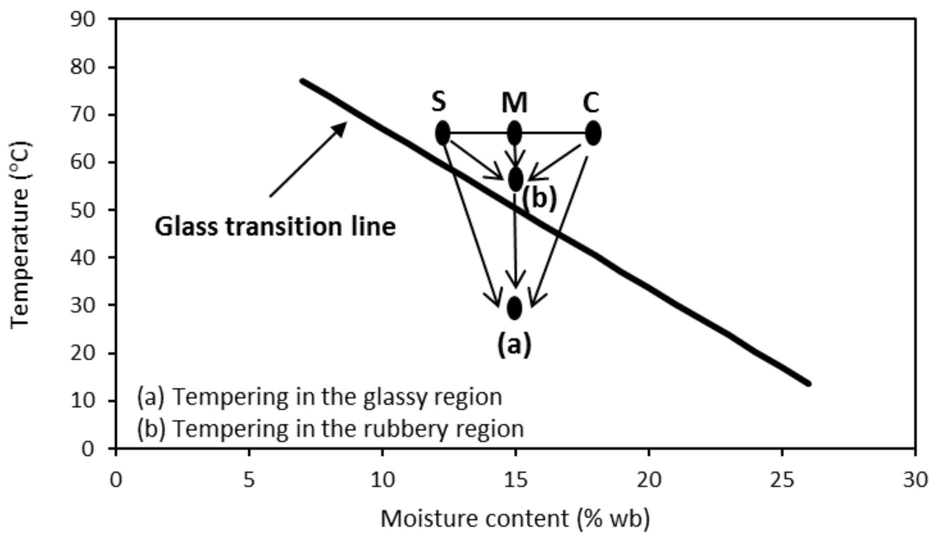

Fig. 3: Hypothetical tempering situations in the glassy region (a) and in the rubbery region (b) for a brown rice kernel that has been dried using air temperatures that initially placed the kernel in the rubbery region.[5] Center (C), mid-point (M), and surface (S) correspond to the kernel locations shown in the inset in Fig. 2.

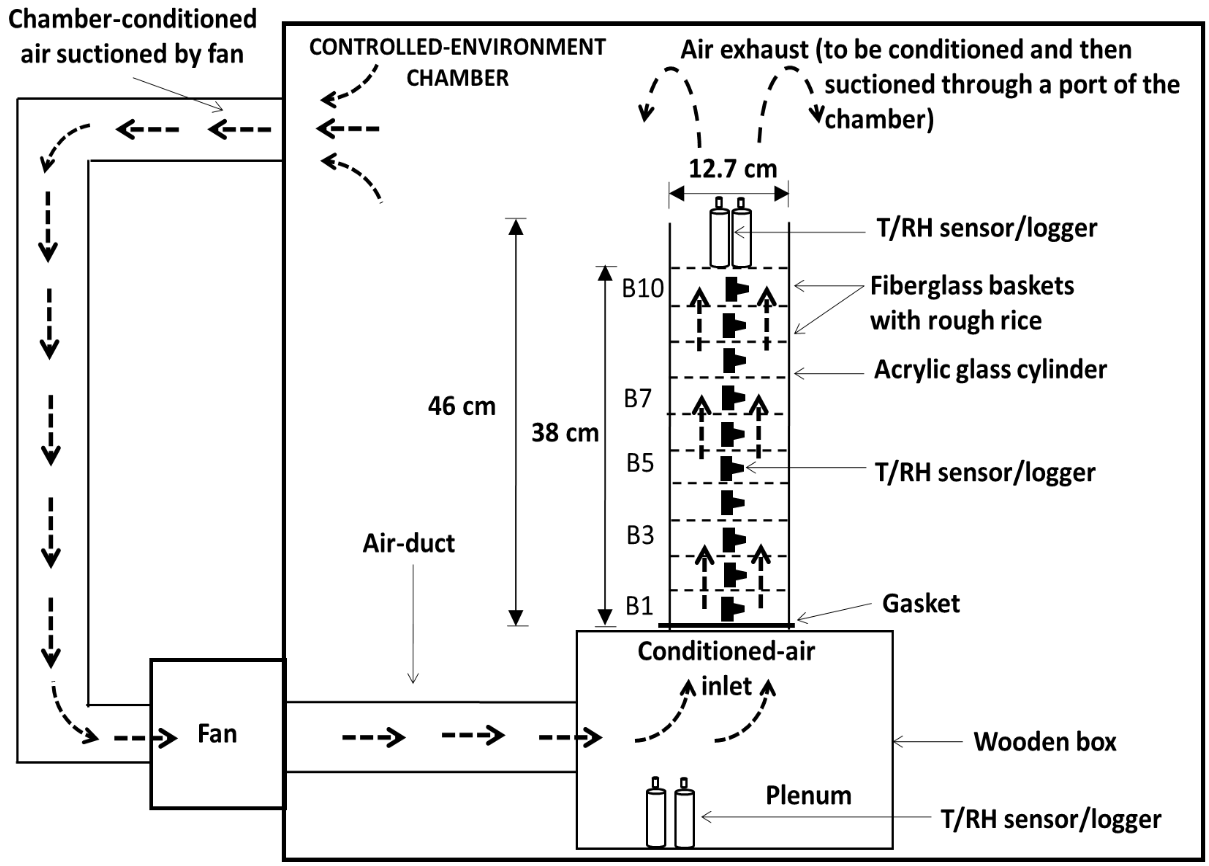

Fig. 4: Schematic diagram of the drying system. The drying assembly comprised a wooden box, an acrylic glass drying column with a metallic screen base, and a set of ten, fiber-mesh cylindrical baskets filled with rough rice and temperature/relative humidity (T/RH) sensors/loggers, all positioned inside a controlled-environment chamber.

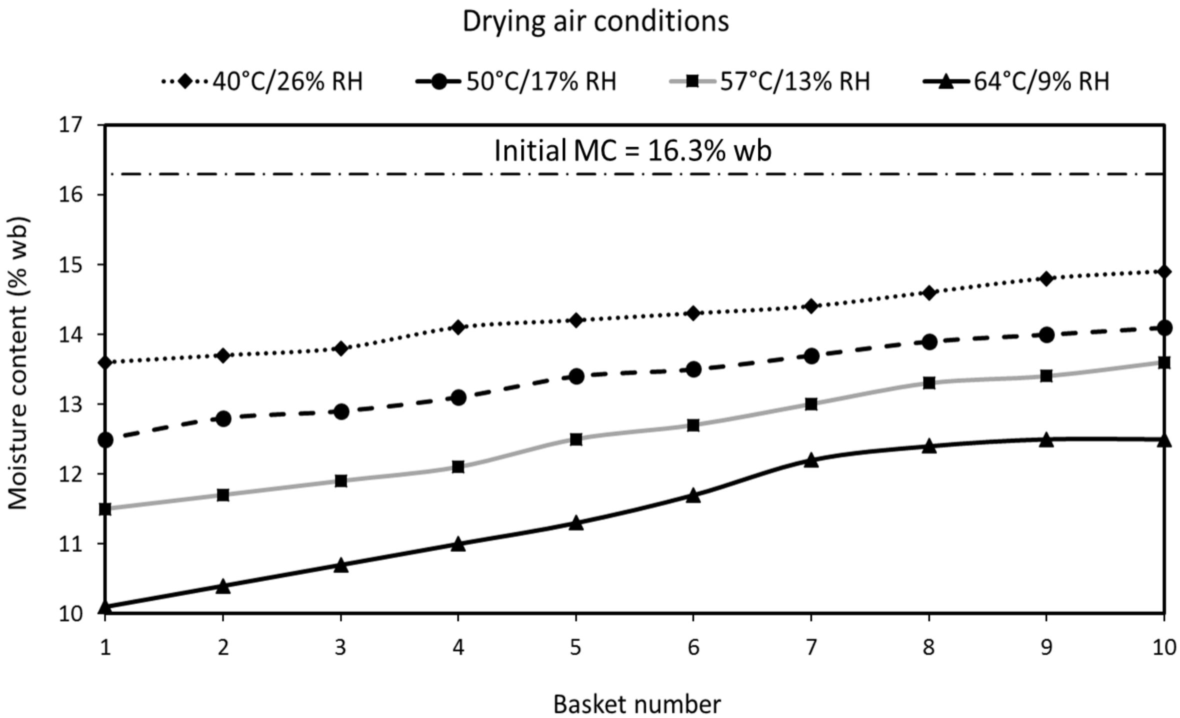

Fig. 5: Moisture content (MC) as a function of basket number within a 38-cm thick rice column after drying long-grain cultivar Roy J for 60 min using the indicated drying air conditions at an air-flow rate of 0.56 $(m^3/s)/m^2$. Basket 1 was nearest to the heated-air plenum. Data points are the mean of two experimental treatment replications.

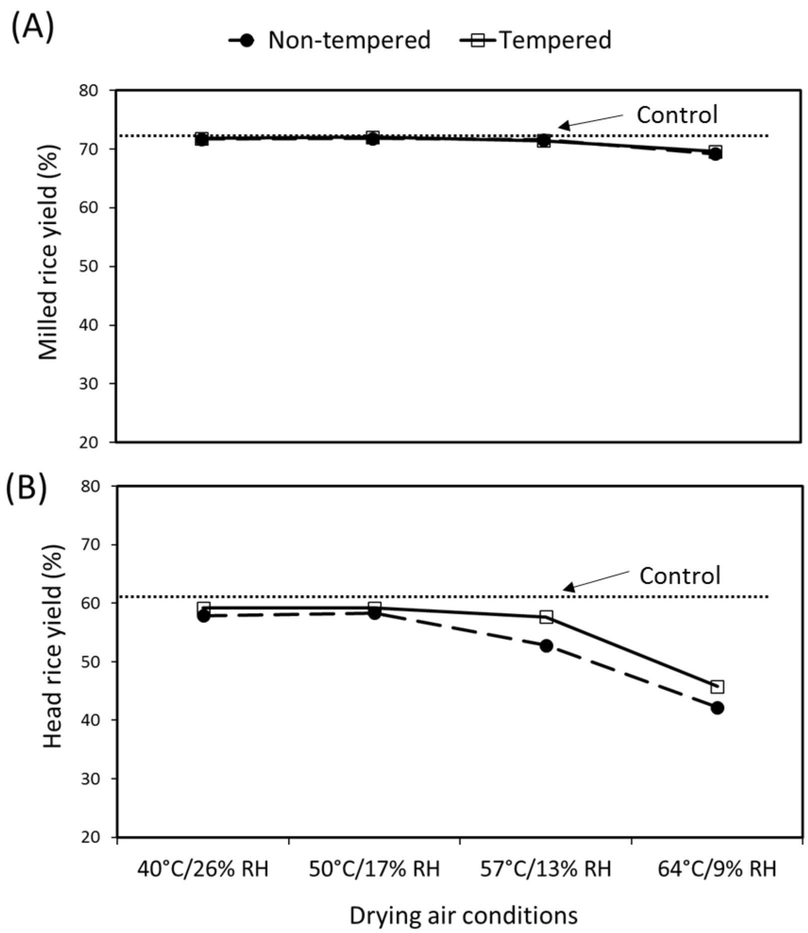

Fig. 6: Milled rice yield (A) and head rice yield (B) of the 38-cm thick bulk column for "non-tempered" and "tempered" scenarios (Table 1). Rough rice at 16.3% initial moisture content was dried for 60 min using the indicated drying air conditions at an air-flow rate of 0.56 $(m^3/s)/m^2$. Data points are the mean of two experimental treatment replications.

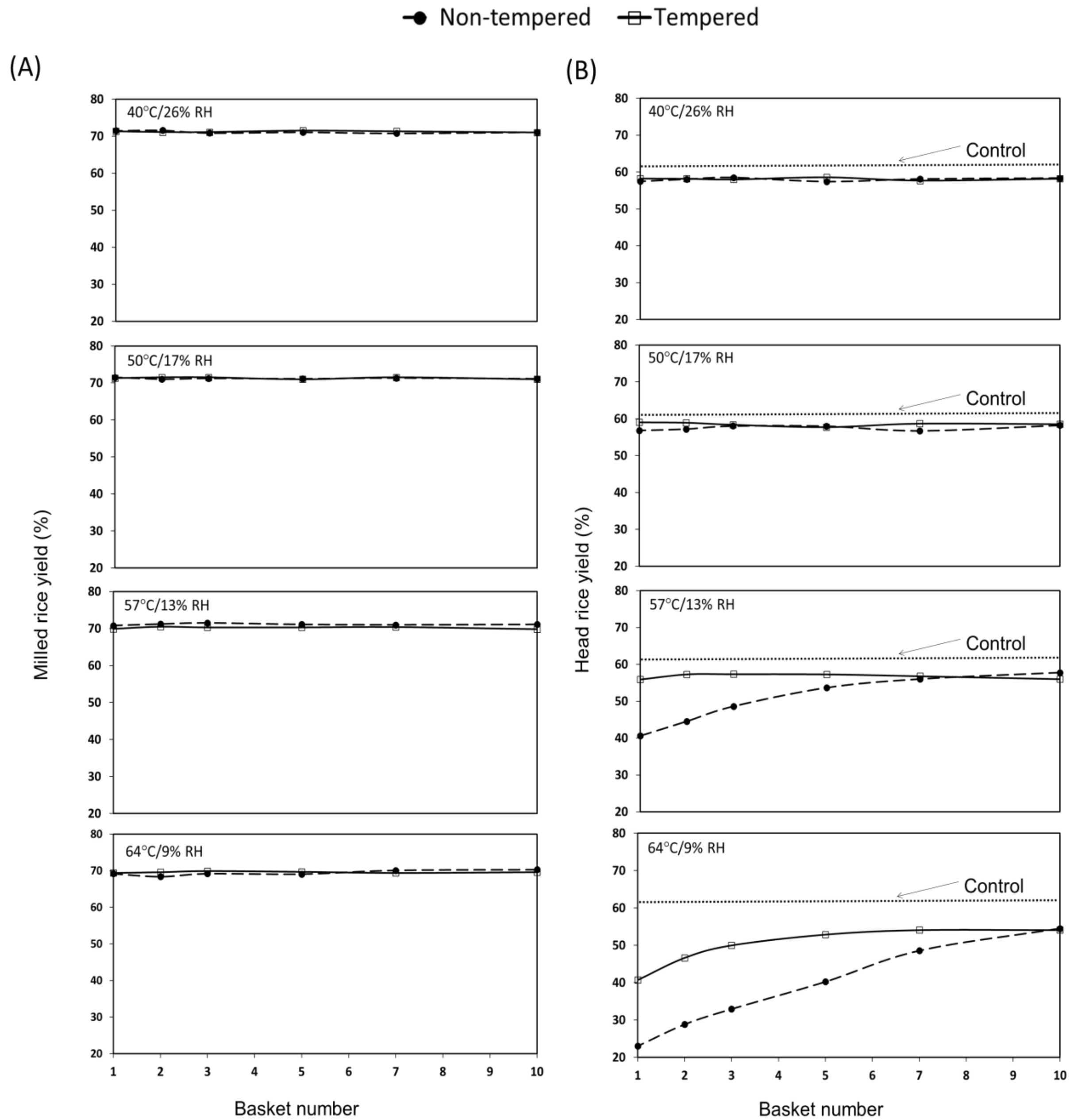

Fig. 7: Milled rice yields (A) and head rice yields (B) of individual baskets comprising the 38-cm thick rice column, with basket 1 being nearest to the heated-air plenum. Rough rice at 16.3% initial moisture content was dried for 60 min using the indicated drying air conditions at an air-flow rate of 0.56 $(m^3/s)/m^2$. "Non-tempered" and "tempered" scenarios are detailed in Table 1. Data points are the mean of two experimental treatment replications.

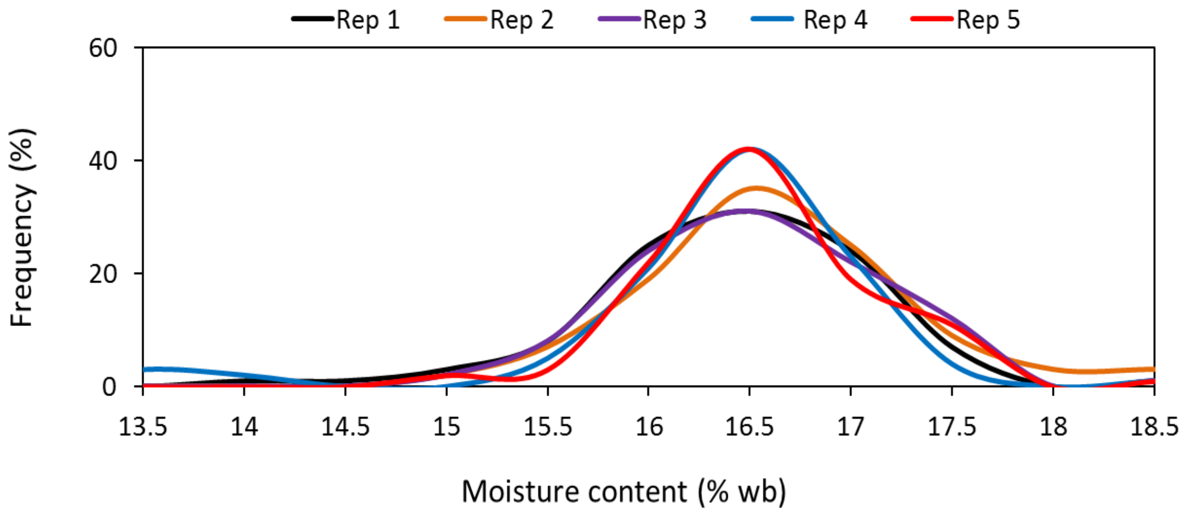

Fig. 8: Individual kernel moisture content (MC) frequency distributions for long-grain rice cultivar Roy J at 16.3% bulk MC. For each replication (rep), MCs of 200 kernels were measured using a single kernel moisture meter (Shizuoka Seiki CTR 800E, Shizuoka, Japan).

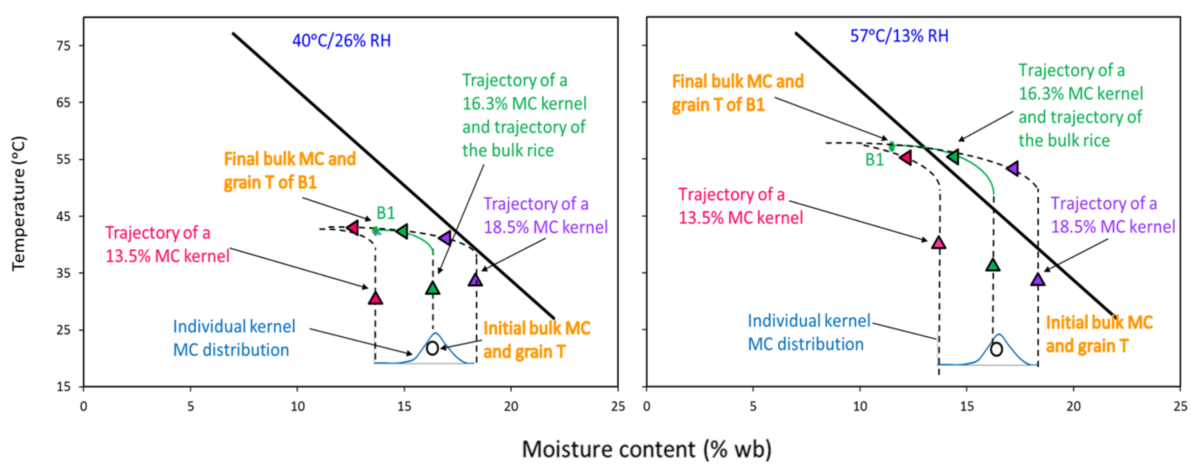

Fig. 9: Initial and final state points, as well as hypothetical drying trajectories of three individual rice kernels and the bulk rice in basket 1 (B1) superimposed on the state diagram at the indicated drying air conditions.

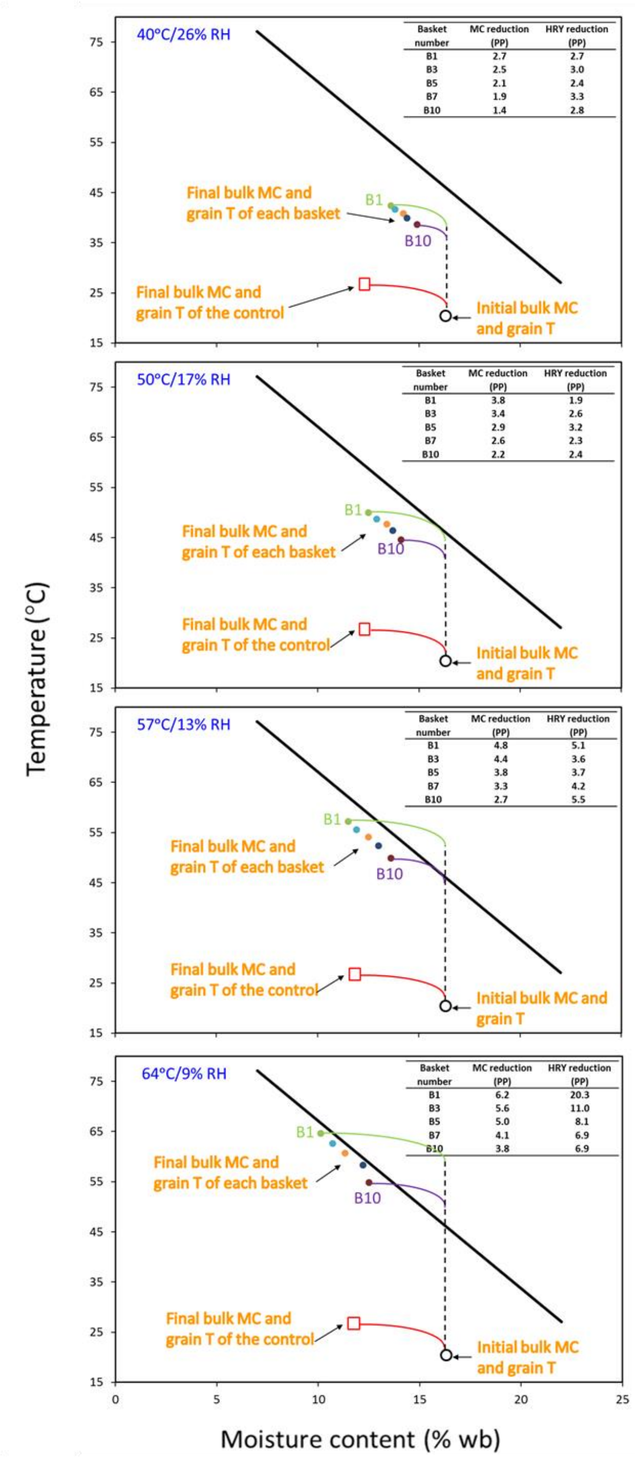

Fig. 10: Initial and final bulk-grain state points of baskets B1 (nearest to the heated-air plenum), B3, B5, B7, and B10 shown on a state diagram along with the "trajectory" of the bulk grain during drying when rough rice at 16.3% moisture content (MC) was dried for 60 min using the indicated drying air conditions at an air-flow rate of 0.56 $(m^3/s)/m^2$. MC reduction and corresponding head rice yield (HRY) reduction of the tempered samples are listed. Data points are the mean of two experimental treatment replications.

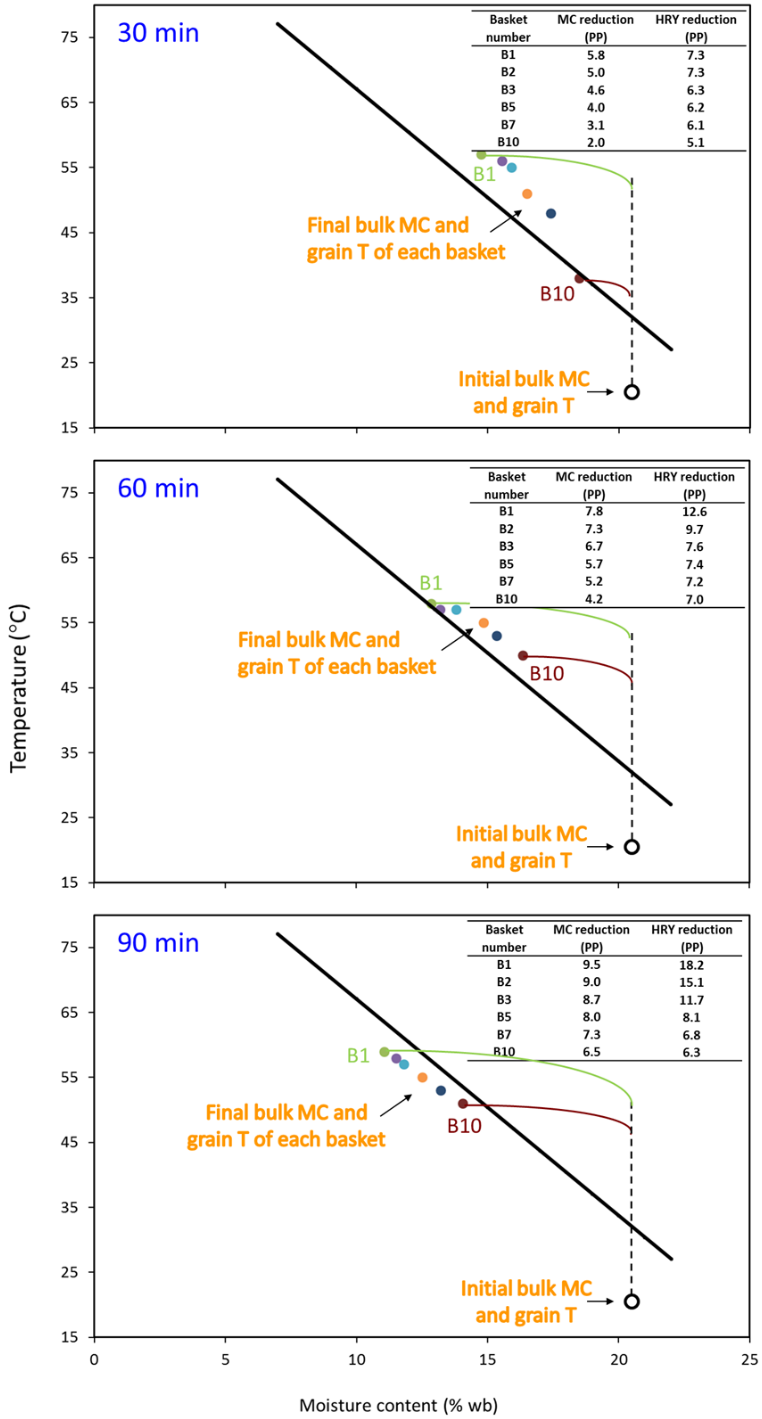

Fig. 11: Initial and final bulk-grain state points of baskets B1 (nearest to the heated-air plenum), B2, B3, B5, B7, and B10 shown on a state diagram along with the "trajectory" of the bulk grain during drying when rough rice at 20.5% moisture content (MC) was dried for the indicated durations using air at 57ºC/13% RH at an air-flow rate of 0.56 $(m^3/s)/m^2$. MC reduction and corresponding head rice yield (HRY) reduction of the tempered samples are listed. Data points are the mean of two experimental treatment replications.

Table 1: Tempering approaches used in this study.

Approach following a drying run		Sample location/type	Procedure
Non-tempered	1.	Bulk column (baskets mixed)	Contents of all ten baskets were mixed, a 500-g sample was spread into a thin-layer on a perforated tray and immediately placed in a chamber maintained at 26°C/56% RH to condition the rice to 12% moisture content (MC).
	2.	Individual baskets	Contents of each basket were spread into thin-layers on individual perforated trays and conditioned to 12% MC, as described above.
Tempered	1.	Bulk column (baskets mixed)	Contents of all ten baskets were mixed, a 500-g sample was placed into a sealed bag and placed in a pre-heated oven at the drying air temperature for that drying run for 4 h, the sample was then conditioned to 12% MC, as described above.
	2.	Individual baskets	Each basket was placed into an individual sealed bag, the ten bags were placed in a pre-heated oven maintained at the drying air temperature for that drying run for 4 h, the contents of each bag were conditioned to 12% MC, as described above.

Table 2: Drying air conditions at the heated-air plenum and final moisture contents (MCs) for the indicated drying air conditions after drying rough rice of long-grain cultivar Roy J at an initial MC of 16.3% for 60 min using an air-flow rate of 0.56 ($m^3/s)/m^2$.

Desired drying air conditions	Actual drying air conditions*	Final MC of the bulk column** (%, wet basis)
40ºC/32% RH	40ºC/26% RH	14.3
50ºC/18% RH	50ºC/17% RH	13.4
60ºC/12% RH	57ºC/13% RH	12.6
70ºC/8% RH	64ºC/9% RH	11.5

*Data from temperature/relative humidity sensors

**Mean of four drying runs

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V. OVERALL CONCLUSIONS

Since the United States (US) rice crop is commonly dried in cross-flow dryers using elevated air temperatures, the purpose of this dissertation was to assess the effect of different drying conditions and tempering approaches on resultant rice milling yields in an experimentally-simulated cross-flow drying column. The three main objectives of this dissertation were to: 1) measure and quantify the effect of airflow rate on the drying air conditions and rice moisture content (MC) profiles within the drying column, and on the material state gradients created within rice kernels during drying, 2) elucidate the effect of tempering approaches on milling yields of rice that had been immediately prior-dried in a system representative of cross-flow drying systems and estimate the minimum tempering duration required to minimize head rice yield reduction (HRYR) in each of the tempering approaches used, and 3) quantify the effects of drying/tempering treatments on the development of intra-kernel state gradients and thus, on the resultant milling yields of rice located at different cross-sections of a drying column during a drying run. The overall aim of this dissertation was to provide useful information regarding the cross-flow rice drying process that could be used to design better rice dryers, and thus, to improve the rice drying process.

For the first objective, the drying air temperature/relative humidity (T/RH) and rice MC profiles inside the experimentally-simulated cross-flow drying column was measured when three airflow rates (Qs) were used during drying. Out of the three Qs used, one Q was 0.46 $(m^3/s)/m^2$, which is typically used in commercial cross-flow rice dryers; thus, the results obtained were representative of typical cross-flow drying scenarios in the Mid-south US. In addition to these results, when the two additional levels of Q were used, the data showed the impact of Q on the drying air T/RH and rice MC profiles during the cross-flow rice drying process. Additionally, the effect of rice initial MC (IMC) and drying duration on the above-mentioned profiles were elucidated. For a particular drying duration, as Q increased, the range of MCs within the drying column decreased. Q also impacted the extents of intra-kernel material state gradients created during drying and thus, had potential impacts on kernel fissuring and consequent HRYR.

To fulfill the second objective, different tempering approaches were followed after prior-drying rough rice in the experimentally-simulated cross-flow drying column. When rice samples were tempered separately after being prior-dried at different cross-sections of the drying column for 60 and 90 min, post-tempering HRYs were much less for samples that had been situated near the heated-air plenum (HAP) during drying than those situated farther into the drying column. Moreover, for the same drying treatment, when the interstitial air from rice from different cross-sections of the drying column was allowed to "interact" during tempering, post-tempering HRYs of rice samples located near the HAP were lesser than HRYs of samples from corresponding cross-sections of the drying column when the samples had been tempered separately. Thus, these HRY results showed the importance of tempering approach in impacting HRYs. Additionally, the severe decreases in HRYs in the rice located near the HAP were the primary reason for the overall decrease of the bulk-column HRYs. Minimum tempering durations were also estimated for the subsidence of drying-induced intra-kernel material state gradients.

To fulfill the third objective of verifying and validating if intra-kernel material state behavior (glassy/rubbery material states) per the glass transition hypothesis can be used to explain the occurrence of fissures and HRYRs in cross-flow drying scenarios, drying air conditions were selected such that different extents of intra-kernel material state gradients would be formed when rice was dried in the experimentally-simulated cross-flow drying column. Post drying, tempering treatments were selected to: 1) either temper the "deep-bed" of rice at an elevated temperature for a sufficient duration so that these intra-kernel material state gradients previously developed during drying would subside during the tempering duration, or 2) not temper the rice after drying. Results showed that when rice kernels were dried using drying air conditions that allowed these kernels to remain in the glassy state, there was negligible HRYR, regardless if samples had been tempered or not. But, when drying conditions were such that the kernels transitioned to the rubbery state during the initial stages of drying and subsequently developed sufficient intra-kernel material state gradients, significant HRYRs occurred in the samples that were not tempered after drying, while HRYRs of tempered samples were significantly less than those of non-tempered samples. Moreover, the effect of tempering on HRYR was more prominent in samples that had been located near the HAP during drying than those located farther into the drying column.

VI. RECOMMENDATIONS FOR FUTURE WORK

The results obtained from the studies comprising this dissertation will contribute towards the knowledge base required for the improvement of the cross-flow drying process. Based on the research of this dissertation, future work could focus on the following aspects:

1) The milling yield data, along with the moisture content (MC) profiles and the drying air condition profiles, of this dissertation can be used to validate mathematical cross-flow drying models and eventually, to be able to use these models to predict milling yields under a range of drying air and rice conditions. Using this milling data in conjunction with such models will provide insights into the role of the glass transition hypothesis in explaining fissuring and resultant head rice yield (HRY) reductions in cross-flow drying scenarios.
2) The studies comprising this dissertation could be extended to incorporate more grain and cultivar types like medium grain cultivars and(or) pureline and hybrid cultivars; this will make this research more practical to the rice industry by providing detailed descriptions of the drying characteristics of commonly grown rice cultivars, thereby making the drying process more predictable.
3) Conducting drying runs in actual cross-flow dryers using different levels of airflow rate will further the understanding of the impact of airflow rate on milling yield, energy efficiency during drying, and dryer throughput; this will allow rice operators to develop recommendations for airflow rates to be used in such dryers.

Ultimately, an optimization study encompassing all three important aspects of the rice drying process, which is the maintenance of HRYs with minimal energy expenditure to dry rice while maintaining a high dryer throughput, is needed.