Air and Rice Property Profiles within a Commercial Cross-Flow Rice Dryer

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Abstract. *Post−harvest processes such as drying can influence rice quality. Drying experiments conducted at the laboratory scale have been used to formulate a hypothesis explaining rice quality reductions; this work needed to be extended and applied to drying conditions encountered at the commercial level. A commercial cross−flow dryer was tested during the 2001 and 2002 rice harvest. The objectives were to record air temperature and relative humidity (RH) data at strategic locations throughout the dryer, obtain samples for rice moisture content (MC) and head rice yield (HRY) analysis at the end of each drying run from sampling locations within the rice column, and determine if rice experienced temperatures above its glass transition temperature (T_g). Above the first grain exchanger, air entering the rice column decreased rapidly in temperature while correspondingly increasing in RH as it passed through the column. However, after passing through the exchanger, lower air temperatures and higher RHs were observed near the hot air plenum (HAP). Rice samples collected next to the HAP showed that in some test runs, over−drying damaged a portion of the rice. For these test runs, rice experienced temperatures well above T_g. For those test runs dried at lower temperatures in which rice did not exceed T_g, negligible HRY reductions were observed.*

Keywords. *Rice drying, Commercial cross−flow dryers, Rice quality, Glass transition.*

Post−harvest handling of rough rice comprises an important series of operations necessary to lower moisture content (MC) to safe storage levels. Rice is usually harvested around 14% to 22% MC (presented on a wet basis) in the mid−South rice growing region of the United States and dried to 12% to 14% MC to minimize microbial activity (Schroeder, 1963) and respiration (Dillahunty et al., 2000). The manner in which rice is dried can affect the kernel physical structure and under certain drying situations, may cause HRY reductions (Cnossen and Siebenmorgen, 2000). Head rice yield (HRY) is the mass percentage of rough rice that remains as head rice after milling; head rice is milled rice kernels that are three−fourths or more of the original kernel length after complete milling (Cnossen and Siebenmorgen, 2000).

In the U.S. rice industry, the cross−flow dryer (fig. 1) is the most prevalent high temperature, continuous flow−type dryer. It requires a smaller pressure drop across the grain column compared to other dryer types such as the concurrent and countercurrent flow (Barrozo et al., 1999). Grain flows by gravity into one of two drying columns, whereby it is initially exposed to heated air that passes through the grain columns perpendicular to the flow of the grain. As the grain flows past the heated air section, it is then exposed to a section in which ambient air is typically forced through the grain column. Unloading augers located at the bottom of the dryer control the retention time of the grain in the dryer. Retention time is varied by the dryer operator depending on the MC of the grain entering the dryer, the drying air temperature, dimensions of the drying column, and the airflow rate (Brooker et al., 1992).

The grain column may have several sections. Each section is usually separated by a grain exchanger. Grain exchangers are used to mix and transfer flowing grain from the heated air side to the exhaust side of the column as it passes through the

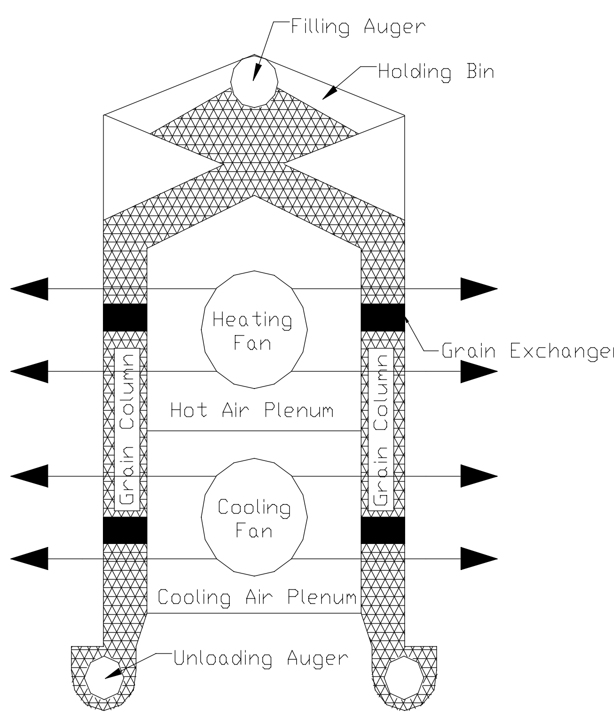

Figure 1. Schematic of a commercial cross−flow dryer adapted from Brooker et al. (1992).

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dryer. Grain exchangers have been advocated as a means of alleviating over− and under−drying of grain. Bakker and Liu (1997) indicated this beneficial effect by examining the variation in MC for maize with and without a grain exchanger for a commercial cross−flow dryer using stochastic modeling. The MC range of maize dried in a non−mixing cross−flow dryer was greater than that of maize dried in a dryer fitted with a grain exchanger. It is generally the case that during drying in a cross−flow dryer, particularly without a grain exchanger, grain located next to the HAP will tend to be over−dried and show reductions in quality. Gustafson and Morey (1981) showed this phenomenon in a study where breakage susceptibility of corn inside the grain column of a cross−flow dryer was studied. They reported that corn located next to the HAP was the first to increase in breakage susceptibility. Breakage susceptibility was strongly dependent on the MC reductions of the dried corn and rapidly increased as the MC reductions increased.

For a given variety, the air temperature, RH, and rice MC are variables that greatly affect the drying of rough rice. During drying, Jia et al. (2002) showed that the air temperature surrounding a kernel could be assumed to equal the kernel temperature within 1.5 min of exposure. Although the designs for cross−flow dryers are not all the same, rice for most commercial cross−flow dryers will be exposed to a heated air condition for several minutes before being mixed by a grain exchanger.

A hypothesis using kernel temperature and MC, as well as principles of polymer chemistry, has been proposed to explain rice fissure formation during the drying process (Cnossen and Siebenmorgen, 2000; Cnossen et al., 2002). This glass transition hypothesis is based on the temperature of localized regions within the kernel relative to the kernel glass transition temperature (T_g). T_g is the kernel temperature at a certain MC in which abrupt changes in material properties, including thermal expansion coefficient, specific volume, and diffusivity can be observed. Siebenmorgen et al. (2004) showed T_g to be inversely related to the average MC of the kernel (fig. 2). Cnossen and Siebenmorgen (2000) showed a reduction in HRY for rice that was dried a substantial amount at temperatures above T_g, thus creating large MC gradients in the kernels, and then suddenly exposing the rice to a condition below T_g. The range of HRY reductions observed varied substantially between different rice varieties and initial MCs.

Although RH is not used to determine T_g directly, it is important in determining the MC of a kernel. At a certain air temperature and RH, an equilibrium moisture content (EMC) can be determined for a particular grain (Stroshine and Hamann, 1994). The rate of drying for a kernel is greatly affected by the difference between its MC and the kernel EMC associated with the drying air temperature and RH; a greater difference will produce a greater drying rate. Although rapid drying may be more effective in removing moisture, the kernel may be damaged resulting in reduced HRY if excessive MC gradients are induced within the kernel (Cnossen and Siebenmorgen, 2000). Drying should therefore consist of finding the optimum drying air condition that maximizes drying rates yet maintains high HRYs.

No previous research was found that obtained air/kernel data within the grain column of a commercial cross−flow dryer. Otten et al. (1980) predicted drying conditions within a commercial cross−flow dryer. This study predicted air temperature, RH, and rice MC profiles within the grain column throughout the dryer; however, no experimental data within the grain column was obtained for validation. The only experimental data obtained was that for air temperature at the heated air inlet and exhaust.

The objectives of the study reported herein were to: (1) measure air temperature and RH data at strategic locations throughout a commercial cross−flow dryer, (2) obtain samples for rice MC and HRY at the end of each drying run from the sampling locations in the grain column to determine changes in rice quality, and (3) determine if the rice in the dryer experienced temperatures above T_g.

Materials and Methods

Sensors (Hobo, Onset Computer Corporation, Bourne, Mass.) were used to measure air temperature and RH in a commercial cross−flow dryer at Jonesboro, Arkansas, during the 2001 and 2002 rice harvest. According to the manufacturer, the sensors had a temperature range from −20°C to 70°C with an accuracy of ≅ 1°C and a measuring RH range from 25% to 95% with an accuracy of ±5%. Sensors were also equipped with data−logging capability. Three elevations

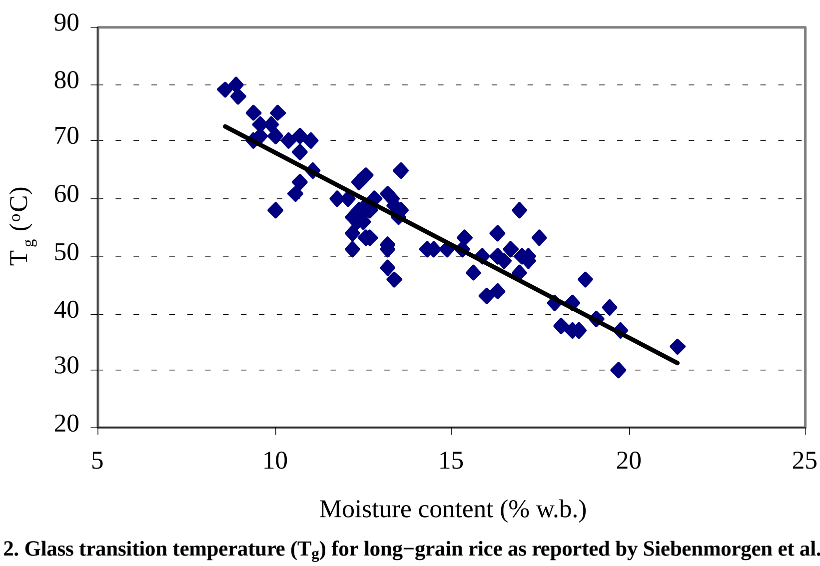

Figure 2. Glass transition temperature (T_g) for long−grain rice as reported by Siebenmorgen et al. (2004).

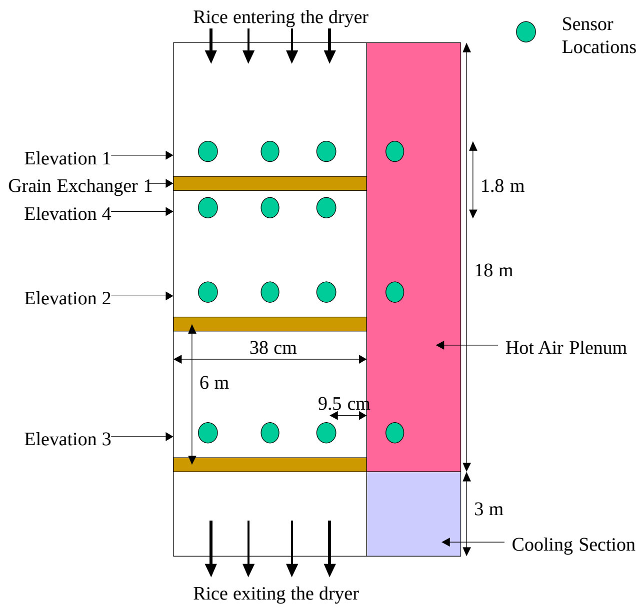

Figure 3. Design layout for the temperature and relative humidity sensor locations in the cross−flow rice dryer for the year 2001 and 2002 test runs. Elevation 4 was later added in the 2002 test runs to determine grain exchanger effects.

approximately 6 m apart were chosen for the 2001 testing runs (fig. 3). At each elevation three sensors were placed equidistant across the 38−cm column of rice. A fourth sensor at each elevation was placed in the HAP. For the 2002 harvest, a fourth elevation was included immediately below grain exchanger 1. Even though this new sampling elevation was the second sampling elevation that the rice encountered after entering the top of the dryer, it was referred to as elevation 4 since it was not included in the 2001 testing. An additional sensor located at the air inlet to the heated air fan measured ambient air conditions.

Sensors could not be placed directly into the rice column due to the force created by the flow of the rice as it moved downward through the dryer. Instead, for sensor placement and sample collection, three 5−cm (i.d.) galvanized pipes were welded to the edge of the rice column end wall (fig. 4) and were spaced equidistant across the rice column at each elevation (fig. 3). The pipe ends extending from the wall were threaded to allow a perforated cap to be easily secured or removed for rice sample collection at the conclusion of a test run. The cap was perforated to allow movement of air through the pipe. To prevent rice from residing in the pipe, a perforated 5−cm (o.d.) plug was placed inside the pipe. The length of the plug was the same length as the pipe to prevent any rice from entering the pipe; this ensured that readings from a sensor were of the air passing through the pipe at a particular rice column location and not of the air passing through stagnant rice in the pipe. The sensors were placed inside the perforated plugs as illustrated in figure 4.

Eight tests were conducted during the 2001 harvest and five during the 2002 harvest. Each test comprised drying a certain lot of rice that took about 8 h to pass through the dryer. Typically, a lot, comprised of long−grain rice varieties, is passed through the dryer several times to reduce the rice MC to between 12% and 13%. Since most moisture is removed during the initial stages of drying, testing primarily consisted of first pass rice. At the end of each test, the caps and plugs

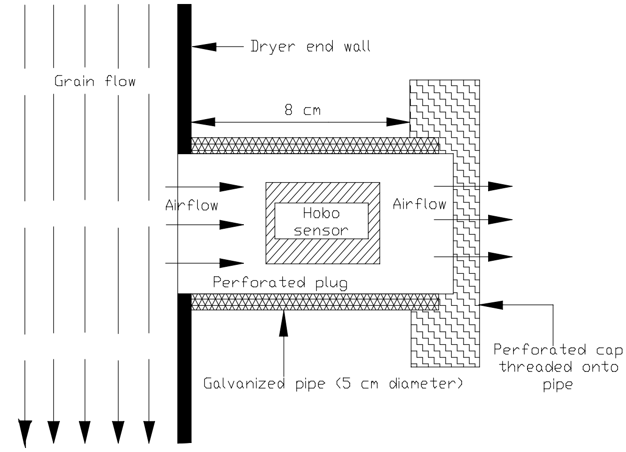

Figure 4. Schematic of a sampling port that was used to house an air temperature and relative humidity sensor and that allowed rice to be removed for moisture content and head rice yield determination.

were removed from the sampling ports to first retrieve the sensors. Once the cap and plug were removed from a sampling port in the rice column, the pressure created by the column of rice and the flow of air through the pipes produced a steady stream of rice exiting the ports from which samples for rice MC and HRY were taken. Additional samples for HRY were obtained at the end of each test run at the dryer inlet and exit to determine an overall effect on quality due to drying.

The testing protocol was: 1) Program the sensors to record air temperature and RH readings 30 min after rice started to pass through the dryer and place the sensors in the desired locations shown in figure 3. This allowed the drying process to reach a near steady state before data was recorded. All sensors were programmed to start data collection at the same time and record data every 10 s. Test run durations were typically 3 to 4 h. 2) Samples for rice MC and HRY were obtained at the end of the test run at the same time the sensors were retrieved. To ensure that the rice sampled at each elevation was from the same portion of a rice lot, sampling at each elevation was timed according to the grain velocity. Grain velocity was determined by applying a coloring dye to a layer of rice and recording the time required for the rice to travel a given distance through the dryer. Samples collected at the end of a run were sealed in an insulated thermos and then placed in an insulated cooler to allow for a slow transition from a warmer to cooler temperature. Rapid cooling of heated rice in which a MC gradient exists within the kernel has been shown to cause kernel fissuring (Cnossen and Siebenmorgen, 2000). Samples for MC measurements were stored in a sealed container to prevent moisture loss until MCs could be determined.

MCs were determined within three days of being sampled by drying 15−g samples of rough rice at 130°C for 24 h using duplicate samples (Jindal and Siebenmorgen, 1987). To determine HRYs, rough rice samples were slowly dried to 12.5% MC by placing samples in thin layers on screen trays in a drying chamber. Chamber air conditions were controlled at 21°C and 55% RH by a commercial temperature and RH control unit (Parameter Generation and Control Inc., Black Mountain, N.C.). After drying, samples were then cleaned to remove any foreign material with a Dockage Tester (Kicker, Mid−Continent Industries, Newton, Kans.). For milling, 150 g of cleaned rough rice was de−hulled using a Satake Rice Machine (THU, Satake Engineering Co., LTD. Tokyo, Japan). The resultant brown rice was milled in a laboratory mill (McGill No. 2, Brookshire, Tex.) for 30 s with a 1.5−kg weight placed 15 cm from the centerline of the milling chamber. Head rice was determined with a Graincheck 2312 Analyzer (Foss Tecator, Eden Prairie, Minn.).

To determine if rice in the dryer experienced temperatures above T_g, kernel temperature profiles at elevation 1 were developed by fitting a third order polynomial trendline (Microsoft Excel 2000, Microsoft Product, Rudmond, Wash.) through the air temperature data obtained from the sensors at elevation 1 at the end of each test run since this was also when rice MC and HRY samples were obtained. A constant T_g value for the rice at elevation 1 was determined for each test run using the MC of the rice entering the dryer since the center of the kernels were postulated to still be at the initial MC when the rice reached elevation 1. These MCs were used to predict values of rice T_g using figure 2.

Results and Discussion

Figure 5 shows the air temperature and RH history at elevation 1 (fig. 3) for the 1 October 2001 test run. A constant RH (4%) was determined in the HAP because the actual RH was below the measuring RH range of the sensor. [The RH in the HAP was determined from the sensor recording ambient air conditions. Using a psychrometric chart and ambient air temperature (15°C) and RH (71%) at 1:30 A.M. for the 1 October 2001 test run, a humidity ratio (7.2 g moisture per kg dry air) was determined. With this humidity ratio and the corresponding HAP temperature of 65˚C, a RH of 4% was determined. Moisture added by natural gas combustion was determined to be negligible.] Changes in sensor readings within the rice column could be attributed to variation in rice MC entering the dryer since negligible changes in temperature readings throughout the course of test runs were observed in the HAP.

Sensor readings at 1:30 A.M. (fig. 5) were used to illustrate air temperature and RH profiles across the rice column (fig. 6). A psychrometric relationship can be observed between these two air parameters. Decreasing air temperatures into the rice column were associated with increasing RHs. This relationship can be explained by evaporative cooling occurring as part of the drying process. Sensible energy is transferred from the air to evaporate moisture from the kernels, thereby cooling the air, but simultaneously increasing the RH.

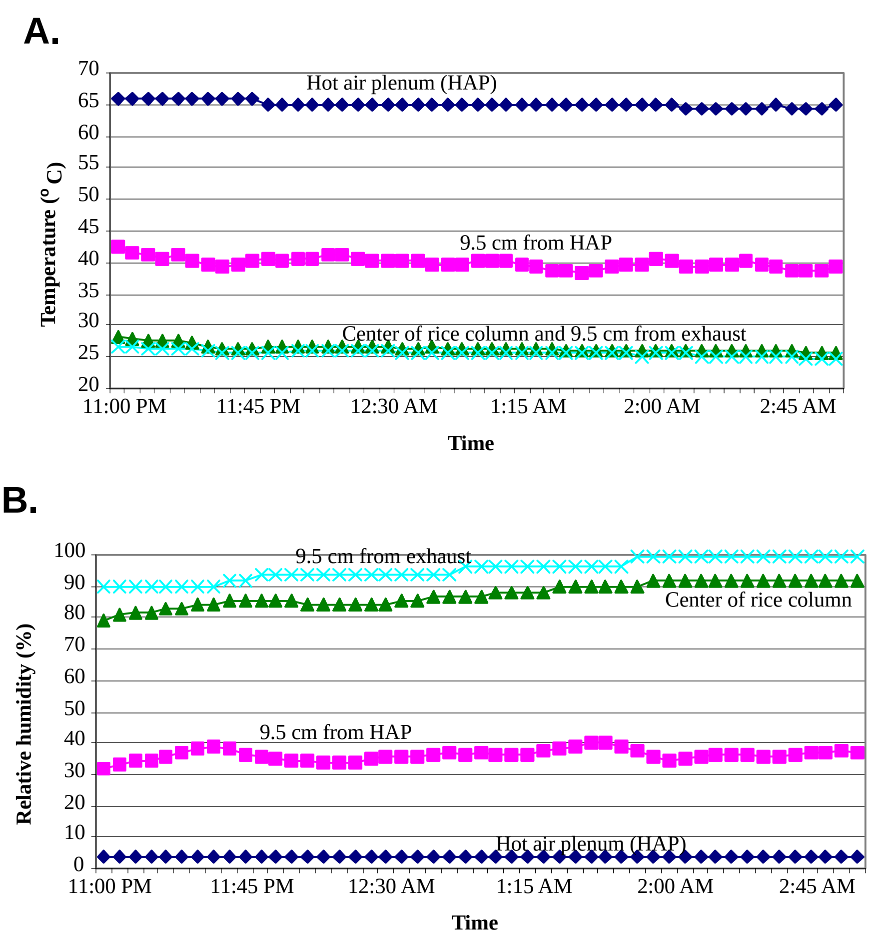

Figure 5. Air temperature (A) and relative humidity (B) history at elevation 1 (fig. 3) during the 1 October 2001 test run. The relative humidity in the HAP (4%) was estimated based on the air inlet temperature and relative humidity.

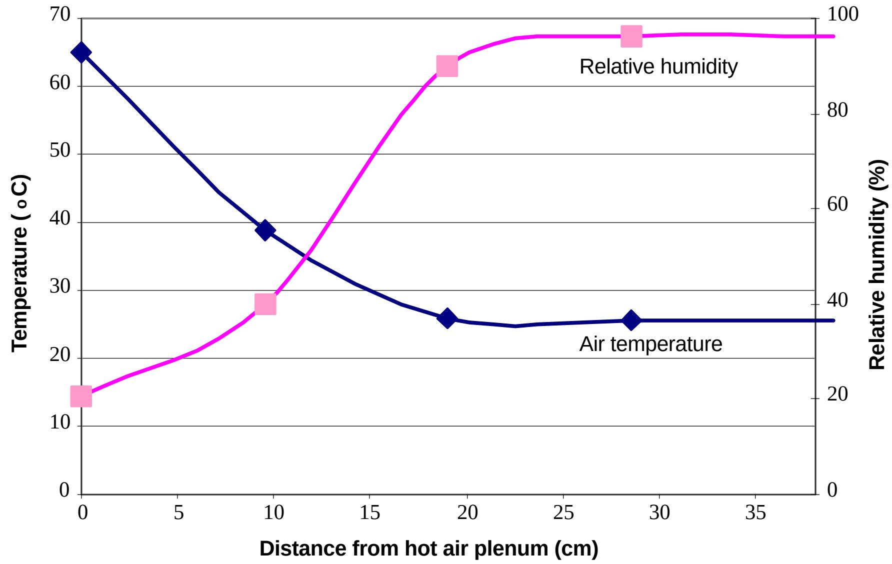

Figure 6. Air temperature and relative humidity profiles at elevation 1 (fig. 3) at 1:30 A.M.for the 1 October 2001 test run illustrated in figure 5.

The sensor located in the HAP recorded a temperature of 65°C, while the sensor located 9.5 cm from the HAP, recorded 40°C. The temperature profile reached steady state near the center of the rice column, illustrated by negligible changes in readings from the sensor located in the center of the rice column and the sensor located 9.5 cm from the exhaust, both of which read about 26°C to 27°C. Correspondingly, the RH increased dramatically from the HAP and also reached steady state near the center of the rice column illustrating that a large portion of rice entering the dryer did not experience any drying effects before the rice encountered grain exchanger 1, located approximately 6 m from the dryer inlet.

Grain exchanger 1 effects can be seen in figure 7, which shows the air temperature and RH readings at 12:00 A.M. for the 11 September 2002 test run. At elevation 4, the

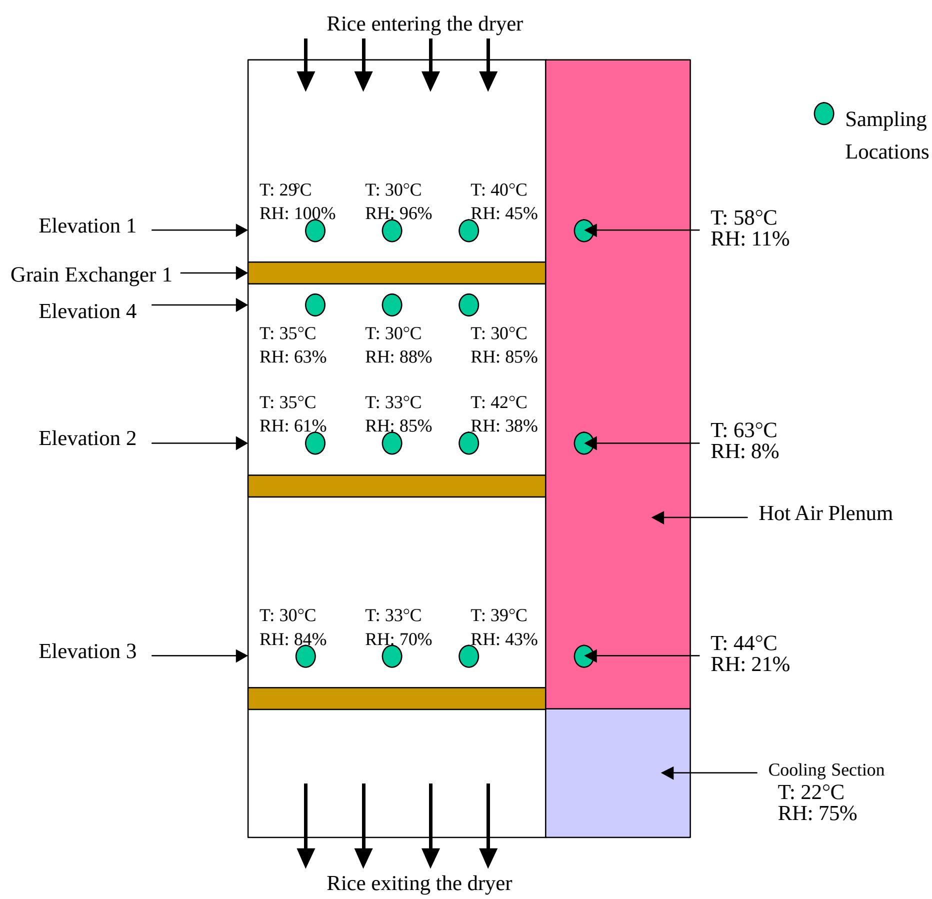

Figure 7. Air temperature (T) and relative humidity (RH) data for various locations within the cross−flow dryer at 12:00 A.M. for the 11 September 2002 testing run. RHs reported in the hot air plenum were estimated using air inlet temperature and RH.

temperature reading of the sensor located near the exhaust (35°C) was higher than the temperature readings of the sensor located near the HAP (30°C) and the sensor located in the center of the rice column (30°C). Correspondingly, the RH 9.5 cm from the exhaust (63%) was lower than the RH near the HAP (85%) and at the center of the rice column (88%). Although it is not completely clear how the rice is mixed within grain exchanger 1, a portion of the rice located near the HAP above the grain exchanger was switched to the exhaust side since a higher temperature and a lower RH reading was observed near the exhaust at elevation 4.

As rice moved down the dryer to elevation 2 (fig. 7), the temperature readings showed a similar trend as the measurements at elevation 1. The highest temperature at elevation 2 was reported near the HAP (42°C) while a negligible difference was observed between the reading reported from the sensor located near the exhaust (35°C) and at the center of the rice column (33°C). However, the RH readings at elevation 2 still did not show a similar trend as the measurements at elevation 1. The RH reading 9.5 cm from the exhaust (61%) was still lower than the RH reading for the sensor located in the center of the rice column (85%). This phenomenon is further addressed in the following paragraph.

Grain exchanger effects were also observed in rice MC profiles. Figure 8 reports the rice MCs for the various sampling locations (fig. 3) obtained at the end of the 11 September 2002 test run. At elevation 1, before rice encountered a grain exchanger, lower rice MCs were observed next to the HAP. Rice entered the dryer at 16.3% MC, which was also the MC observed for the rice sampled closest to the exhaust at this elevation. The MC of the rice sampled in the center of the rice column and near the HAP was 16.0% and 14.1%, respectively. This profile was not observed at elevation 4, located immediately below grain exchanger 1. Figure 8 shows that the highest MC (16.1%) reported at this elevation was for the rice sampled near the HAP while the lowest MC (14.4%) was for the rice sampled near the exhaust. Grain exchanger 1 effects can still be observed at elevation 2, which was located 4 m from elevation 4. The MC of the rice sampled in the center of the rice column at elevation 2 (15.2%) was higher than the rice MC sampled near the exhaust (14.2%). This same pattern was also observed with the RH readings at this elevation, as discussed previously. Due to the fact that heat transfer in kernels is much faster than mass transfer (Jia et al., 2002), it is postulated that although there was sufficient drying time for the temperature readings at elevation 2 to show a similar trend to elevation 1, more time was needed for the RH and rice MC profiles to experience this behavior.

It should be noted that an additional experiment showed that once the caps were removed from the sampling ports 9.5 cm from the HAP, the air passing through the rice column forced rice located closer to the HAP through the sampling port. In this experiment, the sensor located in the sampling

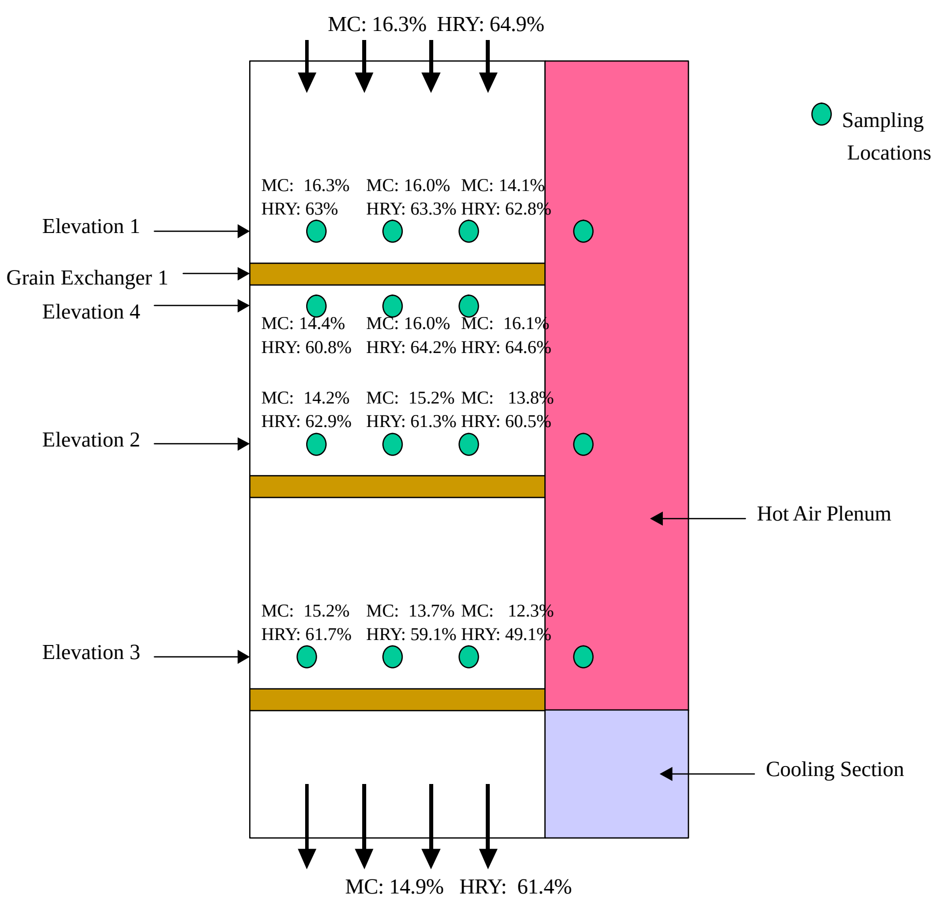

Figure 8. Moisture content (MC) and head rice yield (HRY) data for various locations within the cross−flow dryer at the end of the 11 September 2002 testing run.

port 9.5 cm from the HAP at elevation 1 was removed at the end of a test run and placed in an insulated cooler surrounded by rice that exited the port. Temperature readings were higher for the duration while in the insulated cooler than during the actual drying test run, indicating that rice exiting the sampling port had been located closer to the HAP than the port location. This is expected to affect rice MC and HRY samples obtained from the sampling ports 9.5 cm from the HAP at each elevation.

HRY data reported in figure 8 for the 11 September 2002 test run showed an overall reduction of 3.5 percentage points between the rice entering and exiting the dryer; rice entering the dryer had a HRY of 64.9% while that exiting had 61.4%. Except for elevation 4, the lowest HRYs at an elevation were observed at the sampling locations next to the HAP, which was also where the lowest rice MCs per elevation were reported. This phenomenon was corroborated by Gustafson and Morey (1981), who reported that corn located next to the HAP was the first to increase in breakage susceptibility, which increased as MC decreased for the dried corn. The sampling location at elevation 3 next to the HAP reported the lowest reading in HRY (49.1%) throughout the dryer. This was also where the lowest rice MC (12.3%) was reported.

The relationship between MC and HRY reductions is postulated to be due to glass transition effects (Cnossen and Siebenmorgen, 2000). Figure 9 shows the effects of a severe drying test for the rice dried on 26 September 2001 at elevation 1 where a portion of rice across the rice column experienced a temperature above T_g. This figure shows that the rice located from the HAP to approximately 7.5 cm within the rice column exceeded T_g. Reductions in HRY could be expected for the rice in this portion of the rice column if either drying was continued to produce an over−drying situation or if the rice was switched by a grain exchanger to a cooler air condition. In either case, it is postulated that a portion of this rice having sufficient internal MC gradients will experience differential internal stresses that will create kernel fissures leading to HRY reductions (Cnossen and Siebenmorgen, 2000). Although not illustrated by a figure, a HRY reduction of 8.7 percentage points was observed for the 26 September 2001 test run between the rice entering and exiting the dryer. On test runs where rice temperatures did not exceed T_g, negligible HRY reductions were observed throughout the dryer.

This article discussed only the trends that were observed for a series of tests that were observed in the commercial dryer during the 2001 and 2002 rice harvest seasons. A detailed analysis of all test runs can be found in Schluterman (2002).

Conclusions

Air temperature and RH data were measured inside a commercial cross−flow rice dryer during the 2001 and 2002 harvest. A psychrometric relationship was observed between the air temperature and RH throughout the rice column; decreasing values of air temperature across the rice column were associated with increasing values of RH. Grain exchanger effects were observed from changes in air temperature, RH, and rice MC profiles at elevations immediately above and below a grain exchanger. HRY results were strongly dependent upon the amount of moisture removed, which indicated that sufficient MC gradients had been reached to create kernel fissures. It is postulated the HRY reductions observed could be explained by a T_g hypothesis explaining kernel fissure formation during the drying process. Reductions in HRY were observed for only those test runs that experienced temperatures above T_g.

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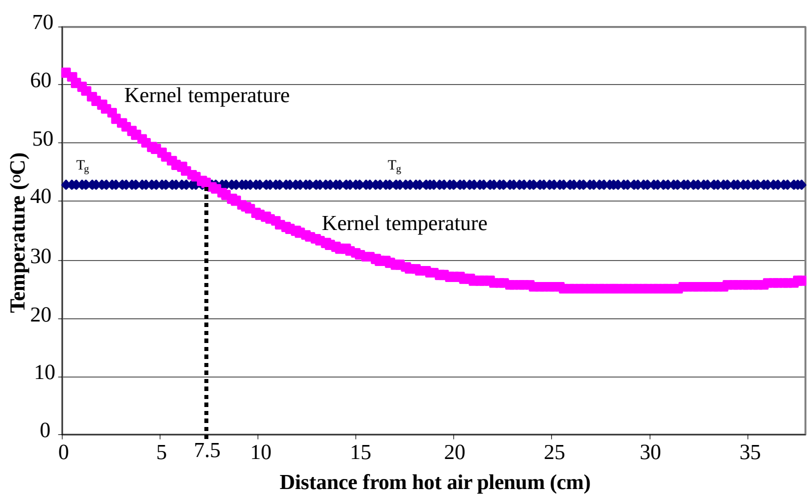

Figure 9. Illustration of an extreme drying case measured on 26 September 2001 in which rice located between the hot air plenum and 7.5 cm inside the rice column at elevation 1 exceeded glass transition temperature (T_g). A constant T_g of 43°C was calculated based on incoming moisture content of 17.8% according to figure 2.

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