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**PROJECT TITLE:**

Infrared Drying of Rough Rice for Improved Quality and Processing Efficiency

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# INTRODUCTION AND OBJECTIVES

Improving head rice yield (HRY) has been an important goal in rice drying research. In last few years, we have demonstrated that using infrared radiation heating from drying can shorten the drying time without compromising the HRY. In fact, we found that HRYs of some rice dried with infrared were even higher that that dried with air. We believed that the higher HRYs were caused by more uniform heating in the kernels (due to heat penetration of infrared radiation heating). A uniform heating is corresponded to low moisture and temperature gradients in the kernel, which are the factors believed to cause kernel fissuring during the drying process. To develop a better understanding of the relationship between these gradients inside the kernel and the HRY, our study focused on accomplishing the following objectives:

1. Determine temperature and moisture distributions in rice kernels under both infrared and convective drying methods.
2. Quantify the fissure rate of rice dried with the infrared and convective drying methods.
3. Establish the relationship between rice milling quality and moisture/temperature distributions.

# MATERIAL AND METHODS

To accomplish the above mentioned objectives, we used three methods to determine the moisture distribution in rice kernels during drying process – Finite Element Method (FEM), Magnetic Resonance Imaging (MRI) and bulk drying experiments. Six drying conditions – ambient air (AA) drying, hot air (HA) drying at 43 ℃ (heated tempering and ambient tempering) and infrared (IR) drying (one, two and three passes) were tested for this study. Details of these methods are explained in the following sections.

### Finite Element Method

Three-dimensional finite element method was be used to model the drying process in a single rice kernel. The rice kernel can be assumed to consist of an axis-symmetric ellipsoids having three isotropic layers: Endosperm, bran and husk. Due to the axial symmetry, an eighth of the kernel volume was considered sufficient to model the drying phenomena in the whole kernel. Physical and thermal properties of the three components, such as density, thermal conductivity, convective heat and mass transfer coefficients, equilibrium moisture contents were used from published literatures. Properties such as effective diffusivity which strongly depends upon the actual drying conditions were estimated by conducting experiments and correlating the observed results to the predicted values. Results of FEM were validated with bulk drying experiments and the trends observed in MRI.

This FEM model is based on the following assumptions:

1. Moisture transport results from the diffusion under the effect of variable moisture content gradients between the different regions in the rice kernel.
2. Germ (embryo) part is very small (~3-4%) and hence not considered as a separate region of rice. It is considered having the same thermal and physical properties as endosperm.
3. Besides water, there are no other volatile materials in the rice kernel.

4. Evaporation of moisture takes place only at the surface of the rice kernel.
5. Contribution of moisture movement to heat transport is ignored, i.e., heat transfer within rice kernel is only due to conduction and infrared radiation.
6. Size of kernel does not change during heating i.e. the shrinkage is ignored.
7. Initial moisture content of the rice kernel is the same throughout the entire kernel.

Governing partial differential equations are:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla.(k\nabla T) + Q$$

$$\frac{\partial M}{\partial t} = \nabla.(D\nabla M)$$

where,

$\rho$ = density of rice, kg/m$^3$

$c_p$ = specific heat of rice, J/(kg. ℃)

T = temperature as function of space coordinates and time, ℃

t = time, s

$\nabla$ = divergence operator

k = thermal conductivity of rice, W/(m. ℃)

Q = volumetric heat generation, W/m$^3$

D = moisture diffusivity, m$^2$/s

M = moisture content on dry basis in fractions, kg water/kg dry rice

Using these partial differential equations with appropriate boundary conditions the model was solved in the Comsol Multiphysics (Comsol Inc., Palo Alto) simulation program, as shown in Figure 1. The solution gives moisture content, temperature and their respective gradients at each time step.

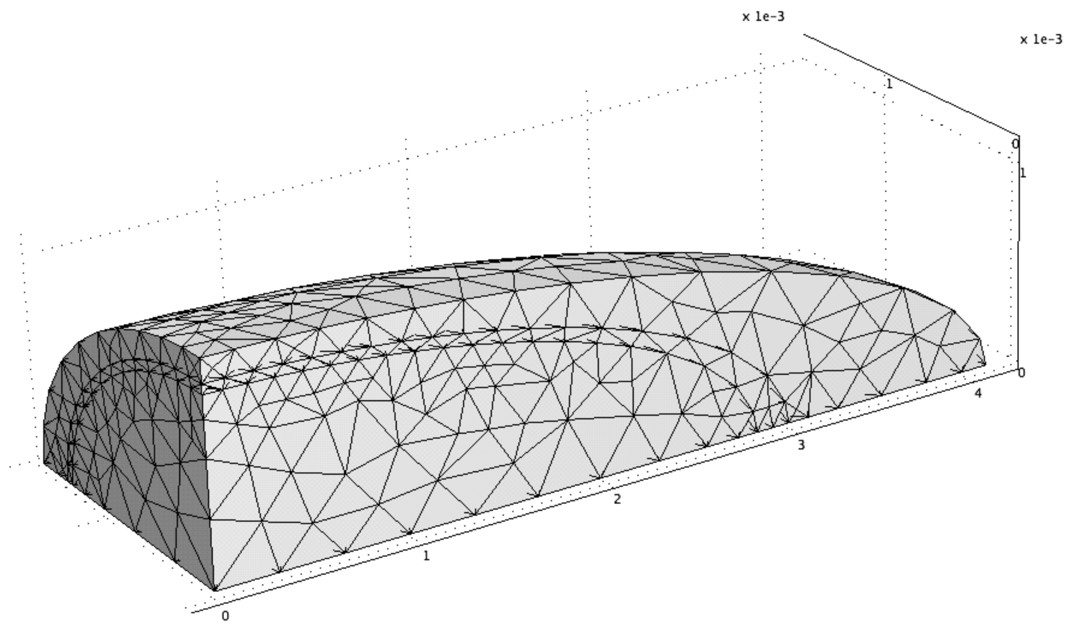


Figure 1: Three dimensional model of rice kernel in Comsol Multiphysics simulation program

**Magnetic Resonance Imaging**

Measuring moisture distribution inside a rice kernel experimentally has always been very difficult, mainly due to its small size. However, with recent advances in MRI technique, the moisture distribution inside the rice kernel can be observed with high resolution. We used a 9.4 Tesla instrument at NMR facility at UC Davis for this study. We were able to get a resolution of about 0.1 mm in our images which means about 15 data points along the shortest axis of rice kernel. The MRI system is shown in Figure 2. We scanned images at regular intervals during the drying process. Since the central plane is expected to have most concentration gradients, we used this plane for further image analysis. We used MATLAB (Mathworks Inc., Natick, MA) program for image analysis. So far, we have conducted ambient air and hot air drying experiments at 43 ℃ in MRI. Rice variety used was Californian M206. In this report, we are discussing findings of only ambient air drying. Images from hot air drying needs to be investigated further to make logical conclusions. Trends observed during MRI of kernels were used to validate the FEM modeling predictions in ambient air drying.

Figure 2: Magnetic Resonance Imaging (MRI) Instrument at NMR facility, UC Davis

**Bulk Drying Experiments**

Californian M206 rice samples were collected from Farmers' Rice Cooperative, West Sacramento on three different days in Sep – Oct 2008 period. These three samples were grown by different farmers and had different harvest moisture contents (HMC) of 22.8%, 24.8% and 26.3% (w.b.). All these three samples were dried by following three methods:

1. Ambient air drying (AA)
2. Hot Air drying (HA) at 43 ℃ – 20 minutes of heating passes with each followed by with four hours of Ambient Tempering (AT) and heated tempering (HT) .
3. Infrared heating (IR) – with 1,2 and 3 passes each followed by heated tempering at final temperature.

Two set of experiments were done when infrared (IR) was used for drying. In the first set, rice was heated by infrared radiations until its kernel surface achieved about 60± 2 ℃ in each pass (up to three passes) with each IR heating being followed by tempering for 150 minutes and cooling at ambient temperature for 40 minutes. The IR heating time used in each pass is shown in Table 1. This 60 ℃ temperature was found to be the limiting temperature beyond which heating results in lower head rice yield. In the second set of experiments, rice was dried for different durations, from 30s to 300s in one pass IR heating. These experiments were conducted to determine the impact of moisture gradients on the HRY.

Table 1: IR heating times used in different passes during IR drying

| | Pass 1 | Pass 2 | Pass 3 |
|---|---|---|---|
| IMC = 26.3% wb | 90 sec | 85 sec | 75 sec |
| IMC = 22.8% wb | 95 sec | 90 sec | |
| IMC = 24.8% wb | 80 sec | 55 sec | |

Final surface temperature reached in any IR method depends upon the intensity used, initial moisture content of rice and the heating time. In this year’s experiments we have used 4000±180 W/m$^2$ of infrared radiation intensity. This intensity is measured at the drying site, i.e. the drying tray location, where rice sample was placed. The dependence of final temperature achieved in IR drying with time is shown in Figure 3. The variation (in vertical direction) in the final temperature is mainly due to variability in initial moisture contents of the samples and differences in samples itself, as they were grown in three different farms.

After these drying treatments, remaining moisture over the storage limit of 14% on wet basis were removed by slow ambient air drying. After the drying, the rice samples were stored in Zip-lock plastic bags to prevent moisture absorption during storage. These rice samples were stored for 15-20 days before they were milled and milling quality was evaluated. Three replicates were used for each treatment.

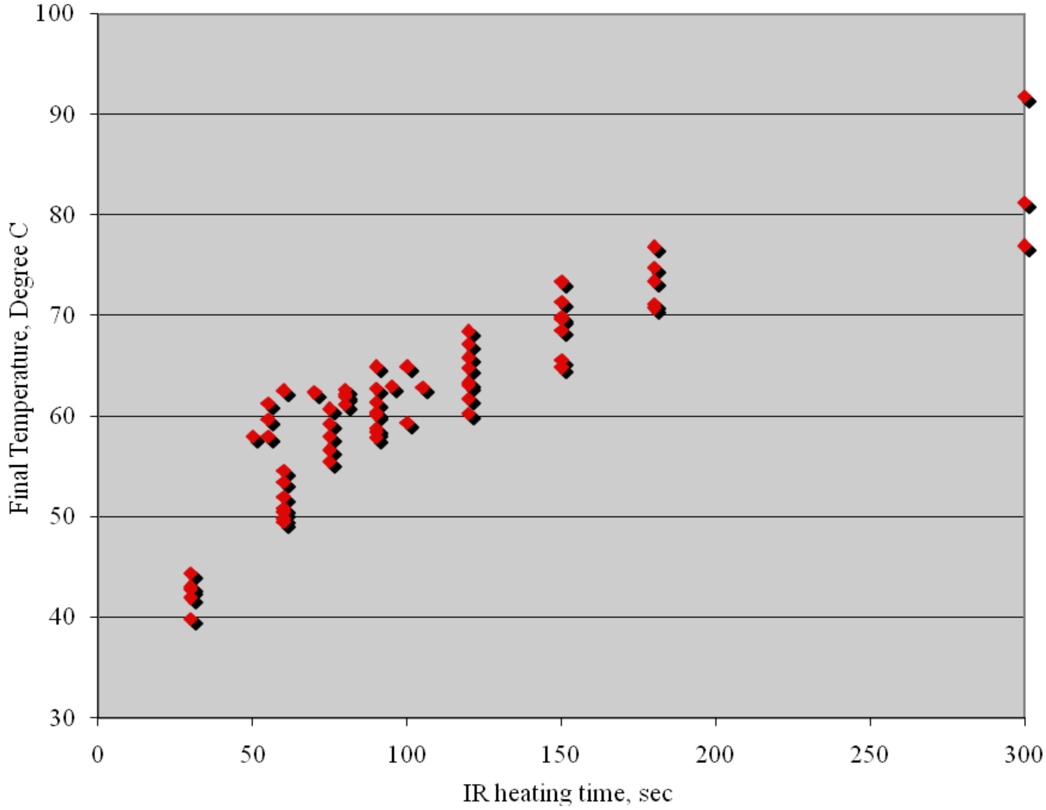


Figure 3: Final surface temperature reached during infrared heating of rough rice having different initial moisture contents at IR intensity of about 4000 W/$m^2$

**Milling Quality Estimation**

All dried rice samples (MC = 12-14% on wet basis) were dehusked using husker (Yamamoto) twice and then milled with rice mill (Yamamoto) in two passes. Head rice yield (HRY), Total rice yield (TRY), Whiteness Index (WI) and Degree of Milling (DM) were measured for each sample. HRY was measured by Grain check analyzer (Foss). For measuring WI and DM, rice milling meter (Satake MM1C) was used.

## RESULTS AND DISCUSSION

### Moisture removal during drying results – Bulk Drying Experiments

Moisture removed in each pass during HA drying is shown in Table 2 and during IR drying are shown in Table 3. In IR drying, the moisture removal values reported here are the total moisture removed during heating, tempering and cooling.

Table 2: Moisture removal (%, on wet basis) during different drying passes in hot air drying

| IMC on wet basis | Drying Method | Pass 1 | Pass 2 | Pass 3 | Pass 4 | Pass 5 | FMC on wet basis |
|---|---|---|---|---|---|---|---|
| 26.3 | HA-AT | 3.5 | 2.6 | 2.4 | 2.3 | 2.0 | 13.5 |
| | HA-HT | 3.7 | 2.6 | 2.5 | 2.1 | 2.3* | 13.0 |
| 22.8 | HA-AT | 3.3 | 2.5 | 1.8 | | | 15.2 |
| | HA-HT | 3.2 | 2.6 | 1.7 | | | 15.2 |
| 24.8 | HA-AT | 3.5 | 2.3 | 1.8 | 1.4 | | 15.8 |
| | HA-HT | 3.4 | 2.4 | 1.8 | 1.5 | | 15.8 |

*This pass was 24 minute pass. All other passes were of 20 minute.
HA – Hot air, AT- Ambient tempering, HT- Heated tempering, IMC – Initial Moisture content, FMC – Final moisture content

Table 3: Total moisture removal (%, on wet basis) during different passes in infrared drying

| IMC on wet basis | Pass 1 | Pass 2 | Pass 3 | FMC on wet basis |
|---|---|---|---|---|
| 26.3 | - | - | - | - |
| 22.8 | 3.5 | 2.7 | | 15.6 |
| 24.8 | - | 2.5 | | - |

In IR drying, moisture measurement was not accurate in some cases and hence the moisture removal values corresponding to some passes are left blank.

**Milling Quality Results – Bulk Drying Experiments**

In this section, milling quality parameters – Head rice yield (HRY), Total rice yield (TRY), Whiteness index (WI) and Degree of milling (DM) in different drying methods are reported. Impact of drying methods on HRY is shown in Figure 4. The three samples with different initial moisture contents (IMCs) were obtained from different farmers, who might have used different agricultural practices and harvested at different times and hence, and there is little variability in their yields (trend in the vertical axis). HRYs in the different drying methods (trends in horizontal direction) are statistically similar, except the HA-AT, which has lower yields. IR methods had the similar HRYs to ambient drying, but much higher than heated air with ambient tempering. These observations are in agreement with our experience in previous years.

Variation in total rice yields (TRYs) in the different methods are shown in Figure 5. HA drying methods have almost the similar TRY as AA drying method while IR methods have the similar or slightly higher yields in all the three kind of samples with different IMCs.

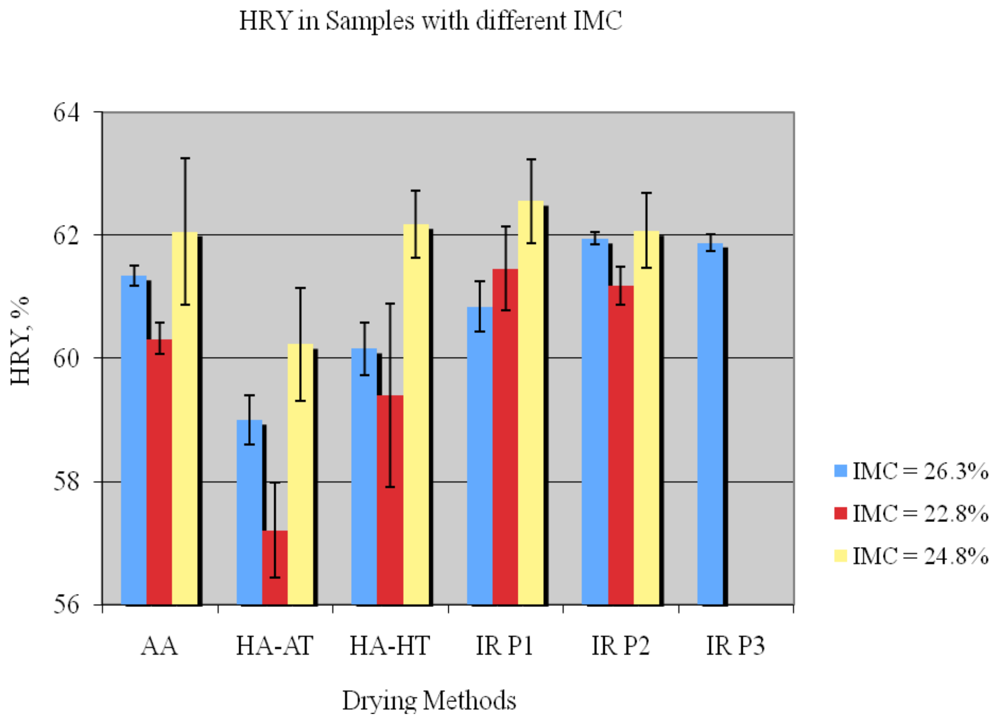


Figure 4: Head Rice Yield (HRY) in different drying methods. IMC: Initial moisture content on wet basis, AA: Ambient Air drying, HA: Hot Air drying, AT: Ambient temperature tempering, HT: Heated temperature Tempering, IR: Infrared drying, P1: one pass, P2: two passes and P3: three passes

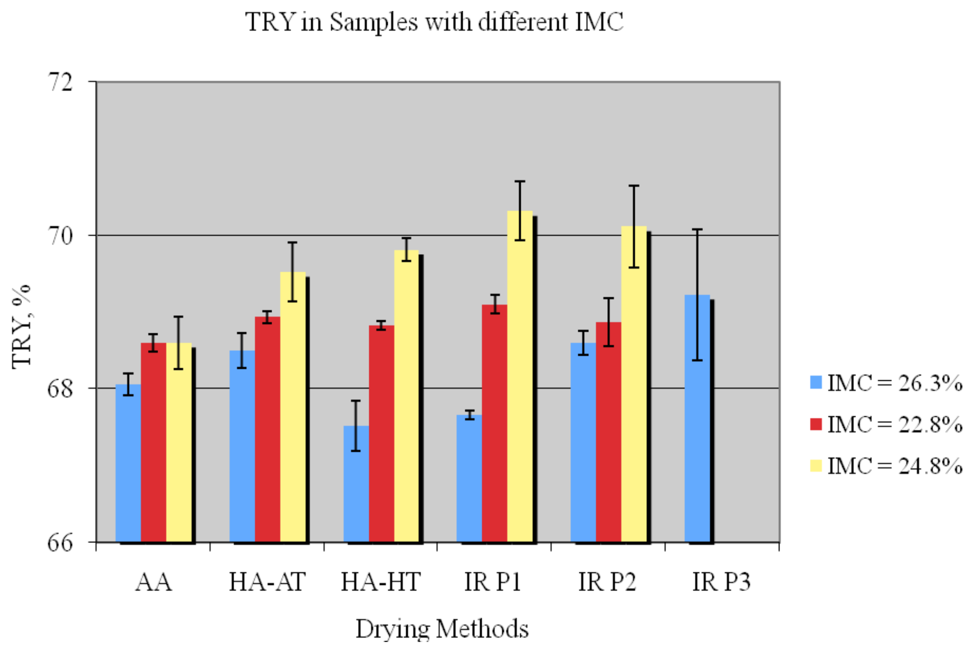


Figure 5: Total Rice Yield (TRY) in different drying methods. IMC: Initial moisture content on wet basis, AA: Ambient Air drying, HA: Hot Air drying, AT: Ambient temperature tempering, HT: Heated temperature tempering, IR: Infrared drying, P1: one pass, P2: two passes and P3: three passes

Whiteness Index (WI) and Degree of Milling (DM) as shown in figure 6 and figure 7, which had identical trends. They were slightly lower in the IR methods than the AA and HA drying methods. Similar results were obtained in experiments conducted in rice harvested in Fall 2007 season.

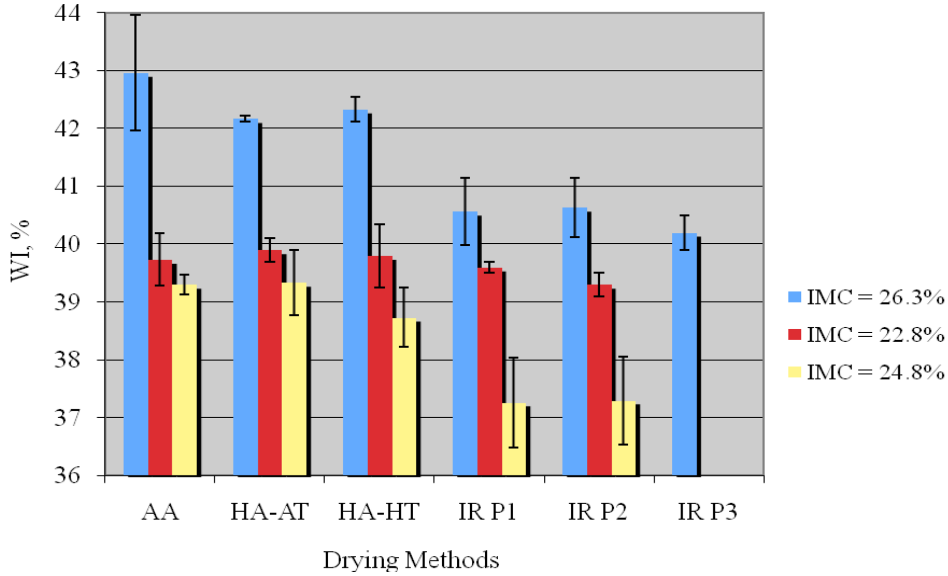


Figure 6: Whiteness Index (WI) in different drying methods. IMC: Initial moisture content on wet basis, AA: Ambient Air drying, HA: Hot Air drying, AT: Ambient temperature tempering, HT: Heated temperature tempering, IR: Infrared drying, P1: one pass, P2: two pass and P3: three passes

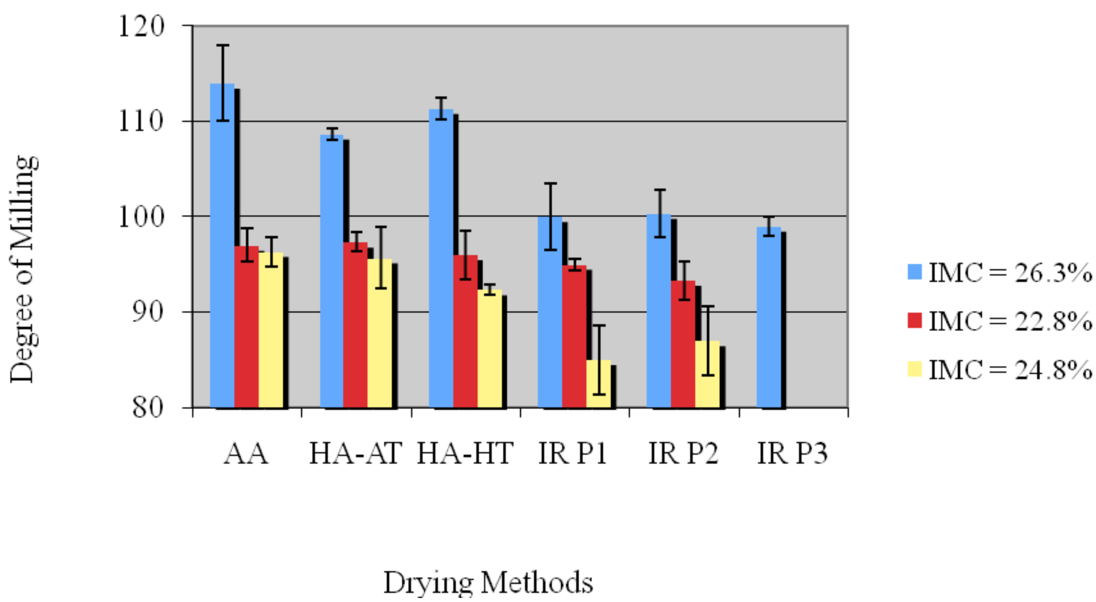


Figure 7: Degree of milling (WI) in different drying methods.

**Moisture Distribution in the rice kernels obtained from FEM Method**

Inhomogeneous distribution of moisture in the kernel causes moisture content gradients (MCG) that ultimately affects the kernel fissuring. In this section, we describe impact of moisture content gradients (MCG) on HRY, a quantitative measure of kernel fissuring. MCGs were obtained by running simulation for the specific drying conditions. Validation of FEM method is described in the next section.

*Ambient Air Drying*

Moisture content (Concentration in FEM) and their gradients at different times are found using FEM modeling. Figure 8 and 9 shows the concentration and their gradients after two hours of continuous ambient air (AA) drying. Initial moisture content of rice was 26.3% on wet basis i.e. 35.7% on dry basis. The units as shown in side colorbar are in dry basis fractions i.e. 0.21 means 21% moisture content on dry basis.

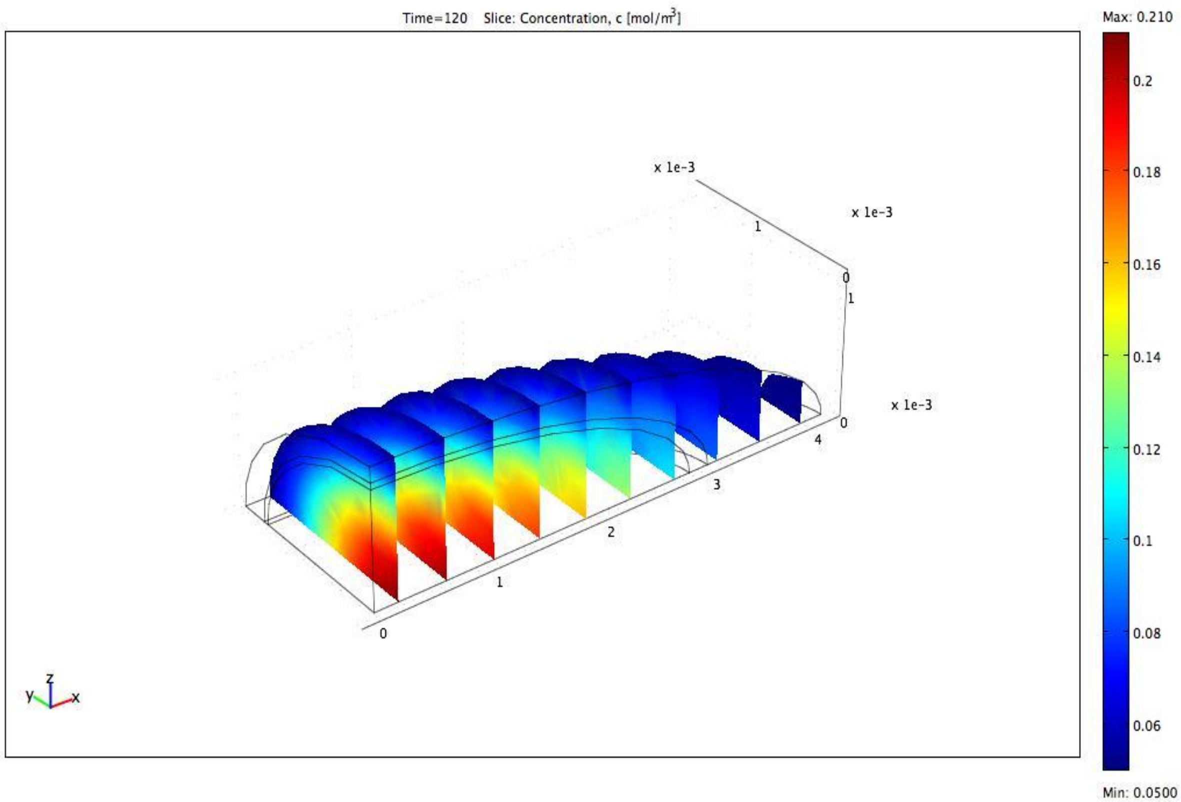


Figure 8: Moisture content ( fraction, d.b.) in rice after two hours of ambient air drying.

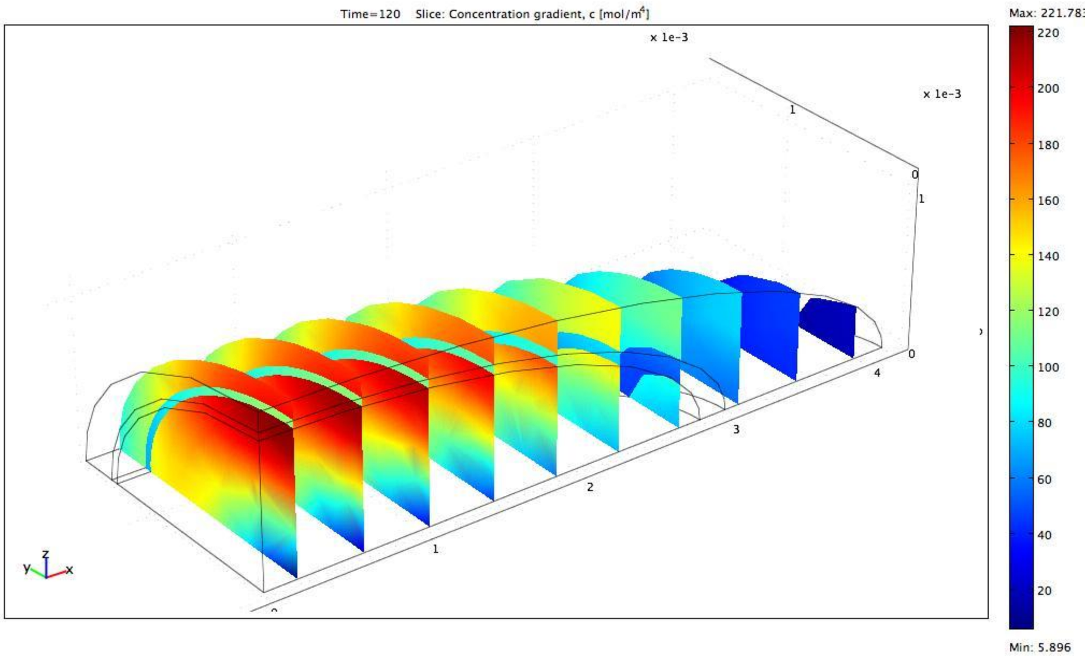


Figure 9: Moisture content gradient (d.b.) in rice after two hours of ambient air drying

Higher moisture gradients are found along the shortest axis of rice (Z-axis in Figure 9) near the center of the kernel. Higher moisture gradients on both sides of the bran layer show the impact of its low diffusivity i.e. high resistance to moisture flow across the kernel. Actual numbers shown on right colorbar have units of moisture content on dry basis in fractions per unit meter. In this units, 140 means gradient of 0.14 per mm or 14% per mm. Since actual elements in the FEM model are on the order of 0.1 mm, it means the difference between moisture content in two adjacent elements is on the order of about 1.4 %.

During the drying process, moisture gradients were calculated at two points, one at bran-husk interface layer (P1) and the other at bran-endosperm (P2), both being in shortest axis direction (in XY plane and close to Z axis). Results are shown in Figure 10. It shows that the MCGs are higher at start of drying at P1 and P2 locations. This is because, endosperm is still at high moisture while the bran and husk regions get dried faster.

Fissures in kernel occur when the mechanical stresses are higher than the strength of kernel. Kernels have higher strength at higher moisture contents i.e. at initial stages of drying. Mechanical stresses are higher when there is higher moisture content gradients (MCG) in the kernel. In ambient air drying method, despite having higher MCG at onset of drying, the kernels does not fissures as it has higher strength also in this stage. HRY obtained in experiments conducted in these conditions was 61.3±0.2 %.

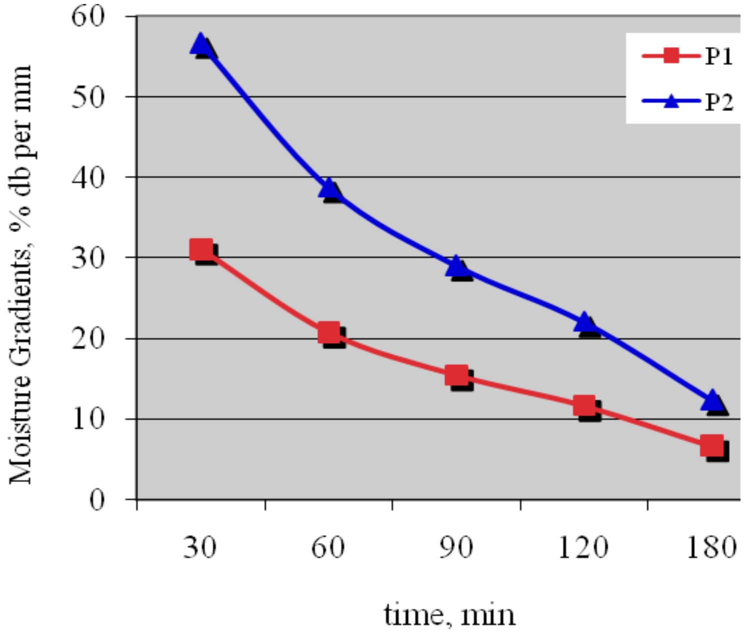


Figure 10: Moisture content gradients at bran-husk interface (P1) and at bran-endosperm interface (P2) during continuous ambient air drying process

*Hot Air Drying*

Same points P1 and P2 (as in AA drying) were selected to study moisture gradients in hot air drying. For this part also, Initial moisture content of rice was 26.3% on wet basis i.e. 35.7% on dry basis. Five passes of 20-minute heating at 43 ℃ was carried out, each being followed by four hours of tempering at 43 ℃. Changes in MCG at P1 and P2 with passes are shown in Figure 11.

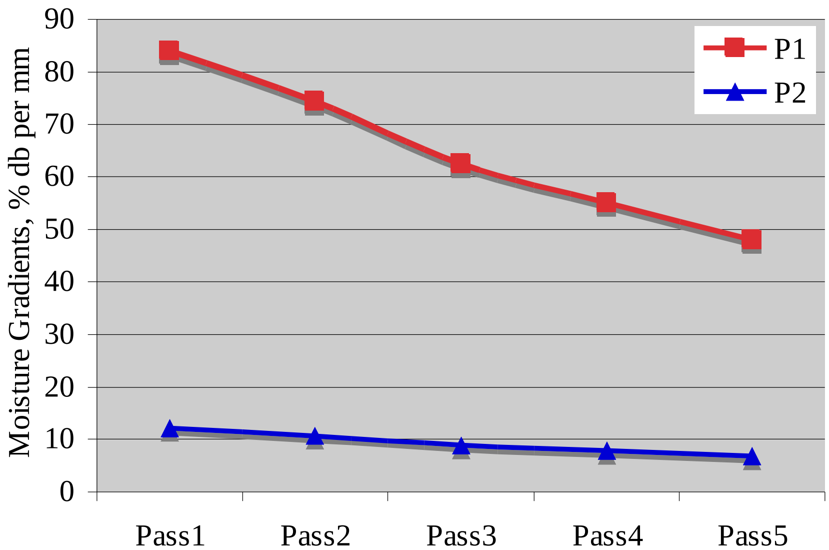


Figure 11: Moisture content gradients at bran-husk interface (P1) and at bran-endosperm interface (P2) after each pass in the hot air drying process

In each 20 minute pass, high amount of moisture is lost from the husk region to the surrounding air while bran and endosperm are still at relatively higher moisture resulting in high MCG for P1 and low MCG for P2. Due to this low MCG for P2, there is little kernel fissuring during this process. HRY obtained in experiments conducted in these conditions was 59.0±0.4 % in case of ambient tempering and 60.2±0.4 % in heated tempering (compared to 61.3±0.2 % in AA drying method).

*Infrared drying*

The same points P1 and P2 were selected to study moisture gradients in infrared drying. For this part, Initial moisture content of rice was 23.5% on wet basis i.e. 30.7% on dry basis. Rice was heated from 30 seconds to 300 seconds under infrared and then tempered for about 150 minutes at 60 ℃. After this, each sample was allowed to cool. Remaining moisture was removed by slow ambient air drying. MCG produced at the end of each infrared treatment and HRY obtained in such experiments are shown in Figure 12.

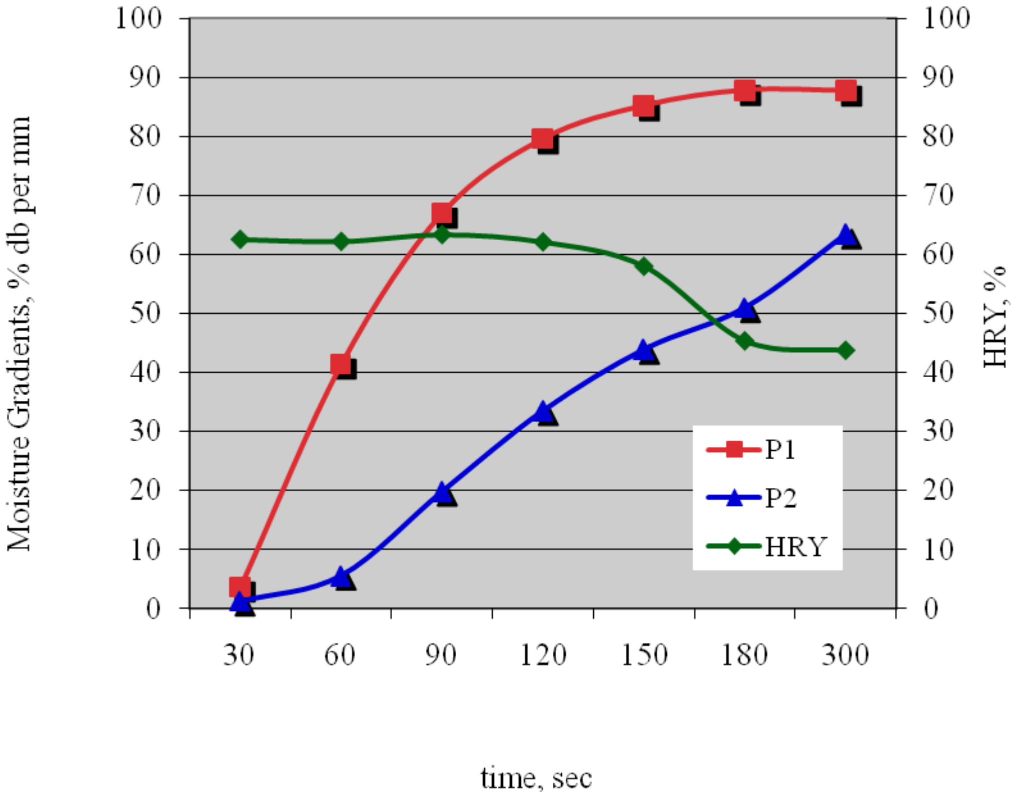


Figure 12: Moisture content gradients at bran-husk interface (P1) and at bran-endosperm interface (P2) during infrared drying process and Head Rice Yield obtained in the experiments conducted in same conditions.

At higher IR heating times, higher MCGs are developed at P2 causing very high stresses in the kernel which ultimately leads to more failure of kernels as evident from HRY plot. HRY starts dropping after 90 seconds IR heating time and hence this is the optimum time for the first pass of IR drying.

In previous studies, we have found that HRY was not affected if IR drying was done in a way so that final kernel surface temperature did not exceed 60 ℃. Using this limit, we dried the rice in three passes. MCGs developed in these passes are shown in Figure 13. In second and third passes initial moisture content is lower and hence we observed lower moisture gradients. In successive passes, the material strength of kernel is lower due to lower moisture; but stresses are also lower as evident by the lower moisture gradients and therefore, there is no much different on HRY in these drying treatments.

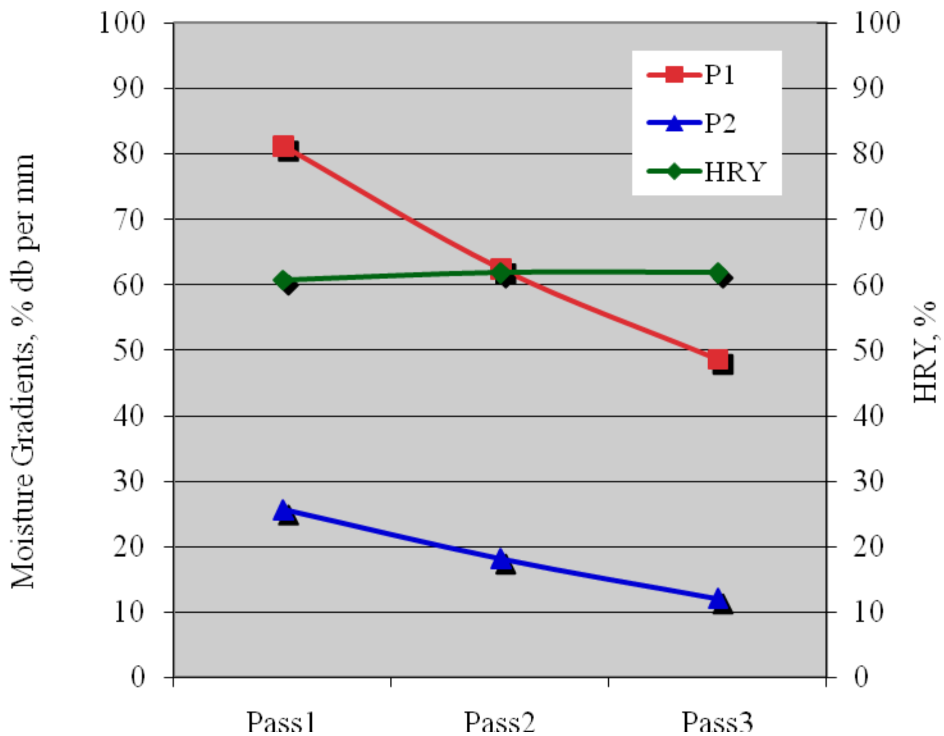


Figure 13: Moisture content gradients at bran-husk interface (P1) and at bran-endosperm interface (P2) after each pass and corresponding Head Rice Yield in the infrared drying process

**Temperature Distribution in the rice kernels – FEM Method**

After running the FEM simulations, we found that rice kernels have very little temperature gradient across the kernel during air drying methods. This is also in accordance with other modeling studies done on other varieties of rice. This is mainly due to the relatively high thermal conductivity of layers of rice, which make rice behave as isothermal body. Within two minutes, center temperature of rice is predicted to attain the kernel surface temperature.

In case of infrared drying, where heating duration is small, there is a possibility of high temperature gradients. But this is difficult to determine this due to unavailability of reliable information on thermal penetration properties of infrared radiation.

**FEM Model Validation – MRI method**

Due to the small size of kernels it is difficult to measure the moisture distribution within the kernel experimentally. This has been one of the biggest challenge in validation of different modeling studies. However, with magnetic resonance imaging (MRI), measurement of the moisture distribution have become feasible both in qualitative and quantitative manner. At this stage, we have been able to develop the method that gives the moisture distribution qualitatively. In this report, we are discussing these results.

We obtained the moisture distribution inside the rice kernel during convective air drying at ambient temperature of 25 ℃ . Single M206 rice kernel was placed in the MRI equipment for this experiment. Figure 14 shows a typical set of images acquired during our experiment. These images were taken at start of drying experiment. It shows the signal intensity along the sixteen parallel slices taken in transverse plane of the kernel. Ring seen in each figure is due to the sample holder. Red color means higher signal intensity while blue means small.

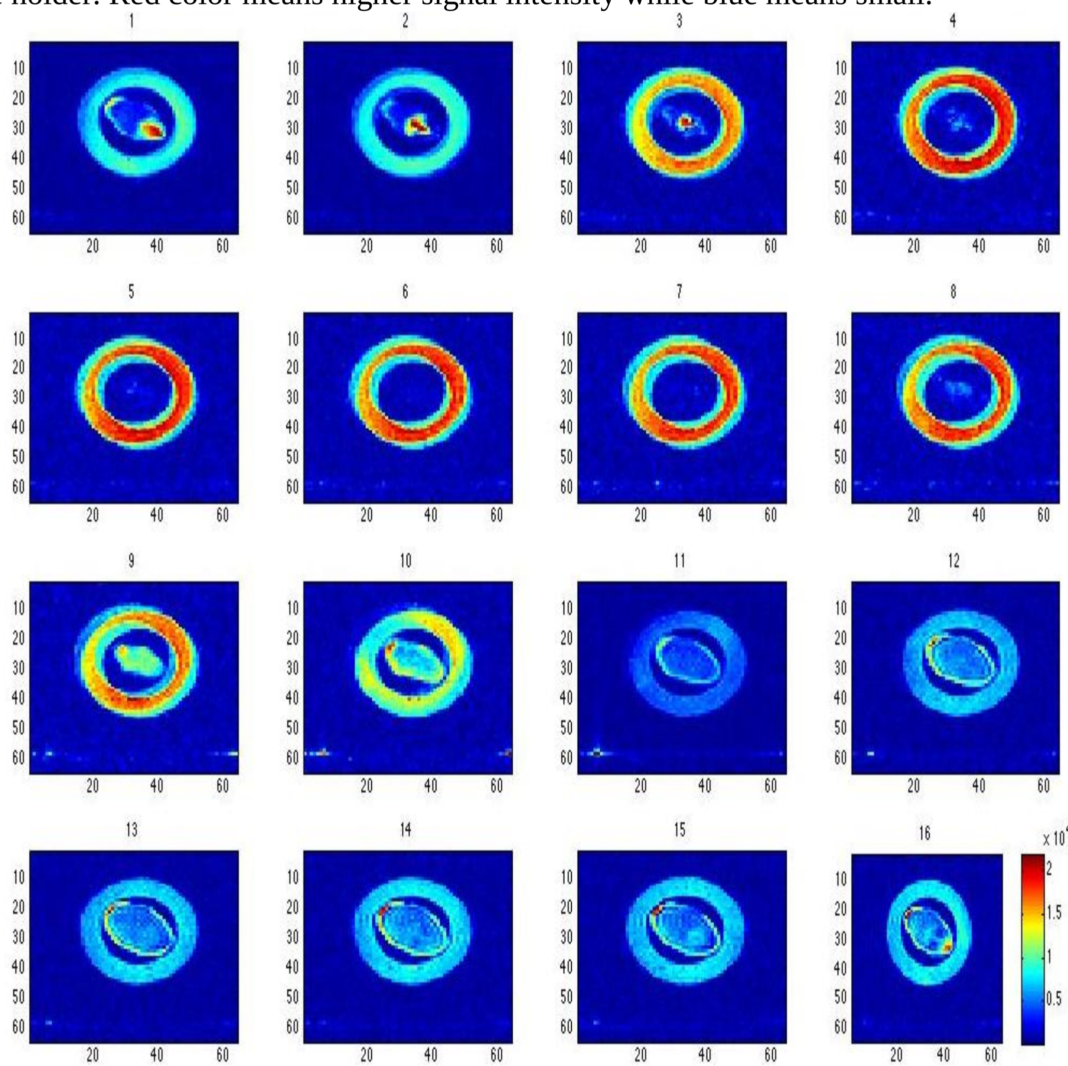

Figure 14: MRI Signal intensity of sixteen slices along the transverse plane at start of drying

Signal intensity is proportional to the moisture and the fat content. Since fat content (found mostly in bran layer) does not change during the drying process, difference in signal intensity with time is a measure of changes in the moisture content. To achieve this, one image is subtracted from the other, pixel by pixel. Each pixel has a numeric value that corresponds to the signal intensity (represented as color for better understanding). Such plots are called subtraction plots. Figure 15 shows three such subtraction plots where, the moisture loss in the center slice (slice No. 12 in Fig 14) of kernel during first, second and third hour of drying are shown. This plot was obtained by subtracting the center slice image at one, two and three hours from the image at start of drying. Image was further processed to reduce the noise signals.

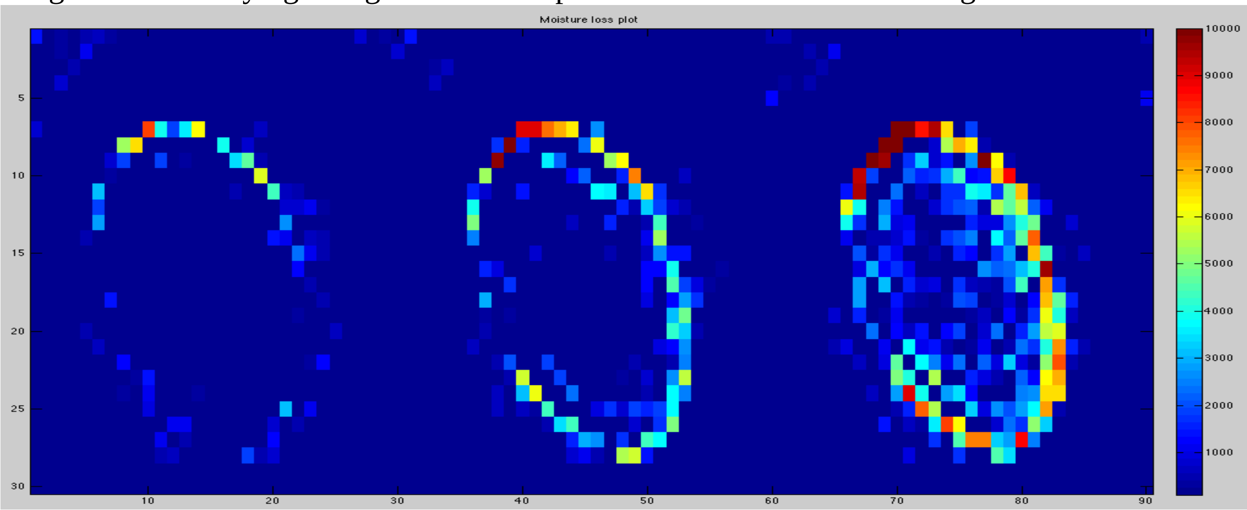


Figure 15: Subtraction plots of center slices in first, second and the third hour of drying

In this figure, moisture loss in the first two hours is mostly in the peripheral region (husk and the bran). Loss of moisture from endosperm is slow and can be seen significantly only in the third hour image. This supports our FEM model prediction as depicted in figure 8, where we found very low moisture in husk and bran while, endosperm has lost very little moisture during initial stages of drying. It is also in accordance with the reported literature and the results of our bulk drying experiments (described in the following section).

**Experimental determination of moisture distribution – Bulk drying Method**

To gain more confidence in our model, we conducted a set of experiments where, we dried rough rice continuously by ambient air (AA) and hot air (HA) drying for 9 and 2 hours, respectively. At regular intervals some samples of rough rice were taken out. For each such sample, moisture content of the rough rice, its husk and its brown rice was determined. Moisture content (on wet basis) of husk, brown rice and rough rice are shown in Figure 16 and 17. These figures show that the husk loses the moisture very rapidly in initial stages of drying while the endosperm and the bran loses moisture almost at the steady rate. These are the same results which we found in our MRI and FEM methods.

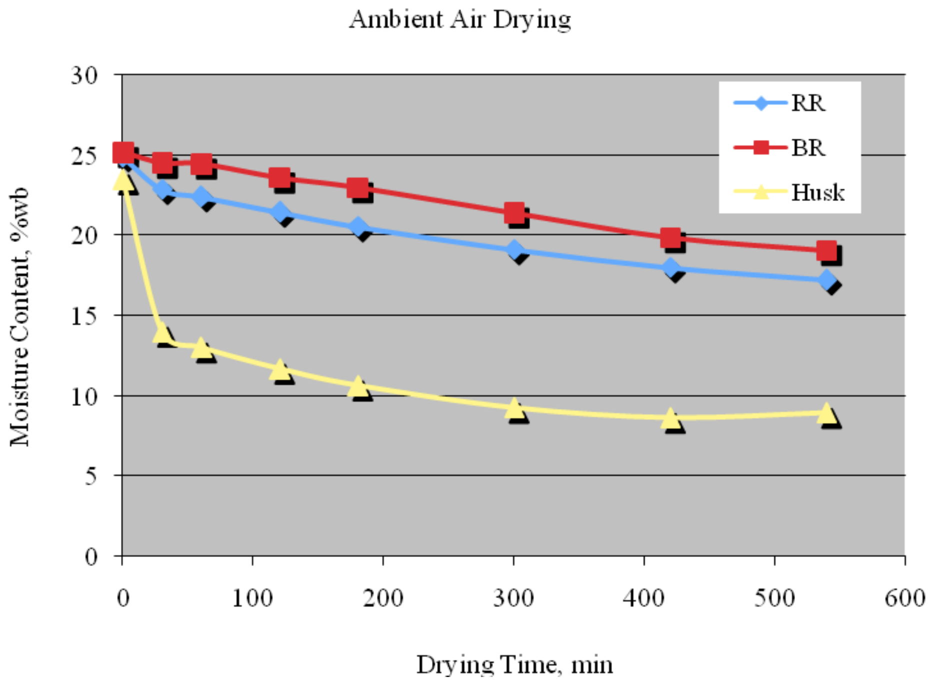


Figure 16: Changes in Moisture content of Rough rice, Brown Rice and Husk during continuous ambient air drying

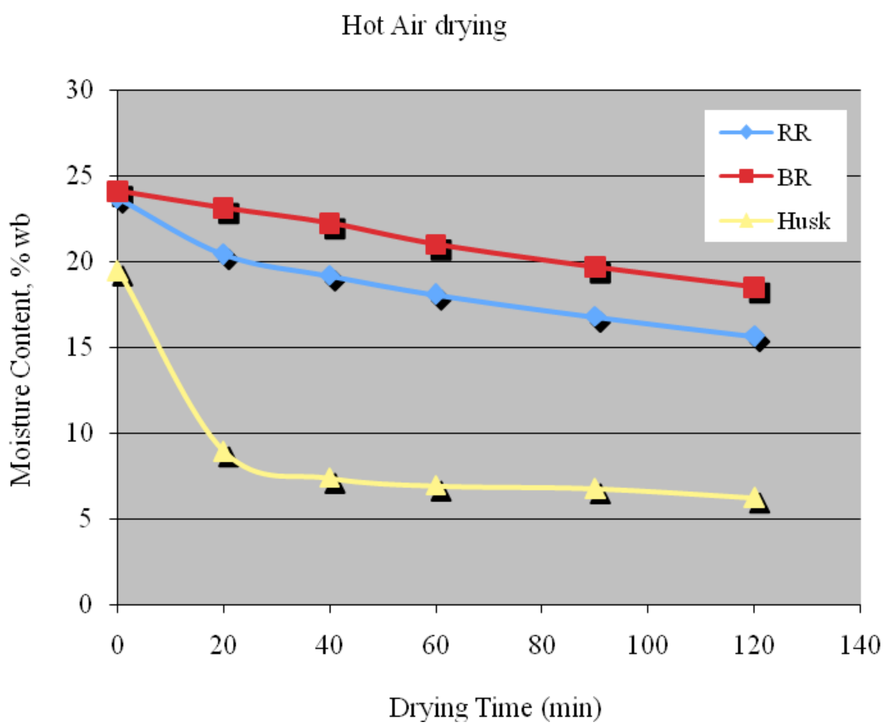


Figure 17: Changes in Moisture content of Rough rice, Brown Rice and Husk during continuous hot air drying

**PUBLICATIONS OR REPORTS**
N/A

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## GENERAL SUMMARY OF CURRENT YEAR'S RESULTS

In this research, we focused on determining the moisture distribution in the rough rice kernel during different methods of drying. We used three different methods to estimate distribution of moisture and moisture gradients in the kernel – Magnetic Resonance Imaging (MRI), Finite element method modeling (FEM) and bulk drying experiments. We also investigated the impact of moisture gradients on milling yields in these three drying methods – ambient air drying, hot air drying and infrared drying.

In bulk drying experiments, head rice yield (HRY) and total rice yield were found to be the similar or slightly higher from infrared drying methods than other methods but the difference was not significant. On the other hand, infrared drying methods have slightly lower whiteness index and degree of milling.

MRI method was used for describing the drying process in convective drying methods, qualitatively. From the MRI images, we found that moisture loss is higher in the husk region than the endosperm during initial stages of drying. This result was further confirmed by findings in FEM and bulk drying experiments.

Using FEM, we found the temperature gradients to be insignificant in the convective drying methods. However, moisture content gradients (MCG) play a significant role in causing the kernel to fissure. High MCG cause more stresses in the kernel. When these stresses become higher than the strength of kernel, it leads to its failure i.e. fissure formation. Strength of the kernel depends on the moisture content and kernels having higher moisture have higher strength. It was found that MCG is higher in drying process at initial stages. However, this doesn't lead to fissure formation as the strength of kernel is also higher due to high moisture content. But if high MCGs are established in the kernel at low moisture contents, it leads to fissure formation. In multi-pass drying methods, MCGs established are lower than the continuous method and hence have higher head rice yield.

When infrared heating time was increased, HRY started dropping after a threshold value. This was due to very high MCGs produced in the kernel. By using optimum infrared heating times in each pass, MCGs were lowered and it was shown to have higher HRYs. This optimum heating time depends on the initial moisture content of rice and was found experimentally. This was the heating time to reach about 60 °C temperature at the end of infrared heating.

The information about impact of MCGs on fissure formation and HRY we learned from this study can be used to optimize and design new drying processes for improved milling quality and reduced drying cost.