ANNUAL REPORT
COMPREHENSIVE RESEARCH ON RICE
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PROJECT TITLE: Rice Utilization and Product Development - Development of High Process and Energy Efficient Infrared Rice Drying Method

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OBJECTIVES AND EXPERIMENTS CONDUCTED BY LOCATION TO ACCOMPLISH OBJECTIVES:

Objectives

This research was a continuation of the previously funded project with an aim at developing new high speed and energy efficient rice drying method using medium-far infrared heating (radiation) in this year. In the past two years, the research focused on using the infrared (IR) and radio frequency for disinfestation. The results showed that the infrared could be used for disinfestation of storage rice with less than 0.5% moisture loss and no milling quality loss. Additional preliminary results also showed that IR could be used to heat rough rice with high harvest moisture quickly and remove a large amount of moisture during heating. Also, because IR heated rice had high temperature, a significant amount of moisture can also be removed during cooling. The literatures also showed that using infrared for rice drying can reduce energy use by at least 30%. All available information indicates that infrared should be a viable technology for rice drying with reasonable capital cost and throughput. However, more comprehensive research needs to be conducted before the technology can be deployed because it is a relatively new rice drying technology.

The specific objectives of the study were:

1. Study the heating and drying rates of rice in single-layer and moisture removal characteristics during cooling; Determine milling quality of IR dried rice.
2. Determine the effect of thickness of rice bed on heating and moisture removal rates and milling quality.
3. Develop recommendations on design and operational conditions of infrared dryers.

Experimental Procedures

<u>Study the heating and drying rates of rice in single-layer and moisture removal characteristics during cooling; Determine milling quality of IR dried rice</u>

Rough rice

Freshly harvested medium grain rice, M202, obtained from Farmers' Rice Cooperative (West Sacramento, CA) was used for conducting the single-layer IR drying tests. The moisture content of rough rice was 25.0±0.3% (high MC) at the harvest. The rice sample with the high MC was equally divided into two portions. One of the portions was slowly dried to 20.6±0.2% (low MC) with room temperature from 17°C to 20°C on the floor in the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis. The thickness of rice bed on the floor was less than 5 cm. During the slowing drying the rice was mixed frequently to ensure uniform drying. It took about three days to reach the 20.6% MC. Then the rice samples with both low and high MC were kept in polyethylene bags and sealed to ensure no moisture loss before they were used for the IR drying tests. The rice samples were further divided into 250 g samples with a sample divider at the test time. All reported moisture contents are on wet weight basis and determined by the air oven method (130°C for 24 h) (ASAE, 1995).

Infrared heating treatment

A catalytic emitter provided by Catalytic Industrial Group (Independence, Kansas) was used as infrared radiation source. The emitter generated IR radiation energy by catalyzing natural gas to produce heat along with small amounts of water vapor and carbon dioxide as by-products. The dimension of the emitter was 30 x 60 cm with surface temperature at about 730°C and corresponding peak wavelength of 3.6 μm assuming a blackbody. An aluminum box with dimension of 65 cm (length) x 37 cm (width) x 45 cm (height) was installed around the emitter as wave guide to achieve a uniform IR intensity at the rice bed surface. The rice bed was set at 5 cm below the bottom edge of the wave guide. The average IR intensity at the rough rice bed surface was 5348 W/m^2, which was measured by using Ophir FL205A Thermal Excimer Absorber Head (Ophir, Washington, MA). The drying bed was made with a 3 mm thick aluminum plate for minimizing the radiation energy loss through the drying bed due to its high reflectively. The reflected radiation energy could also be used to heat the bottom side of rice kernels. A piece of plywood was installed beneath the aluminum plate for reducing the energy loss through conduction. In the drying tests, a 250 g rice sample was placed on the drying bed as a single layer with corresponding calculated loading rate of 2 kg/m^2.

Both high and low MC rough rice samples were used for the drying. For measuring the drying characteristics and milling quality, eight rice samples were heated for each of the four time durations, 15, 40, 60 or 90 s with initial drying bed surface temperature of 35°C. The rice sample weights were measured with a balance with two-decimal accuracy before and after heating. The weight loss during heating and the original moisture content were used to calculate the moisture removal during the heating periods. The moisture removal was calculated as the difference between the original MC and the MC after treatment and reported as percentage points. Control samples for milling quality comparison were produced by drying the high and low MC rough rice samples using room air to 13.6% from the original moisture contents.

Tempering and cooling treatments

In order to study the effects of tempering on moisture loss during cooling, and milling quality, both tempered and non-tempered samples were prepared. Half numbers of the heated rice samples were tempered and the rest of the samples were cooled without tempering in the laboratory. The tempering was conducted by keeping rice samples in closed containers placed in an incubator with a temperature as same as the heated rice for 4 h immediately following the heating. Four samples were each cooled using natural cooling (slow cooling) or forced air cooling at room temperature of 20°C to 24°C as a thin layer (about 1 cm thick). For natural cooling, the thin layer of rice was placed on a laboratory bench for about 30 min. For forced air cooling, the samples were placed on mesh trays and cooled by blowing room air through the bed with air velocity of 0.1 m/s. All forced air cooling samples were cooled for 5 min. After the natural and forced air cooling processes, the temperatures of rice samples were close to the room air temperature. The sample weight changes caused by the cooling treatments were recorded at the end of cooling and used to calculate the moisture removal based on the moisture contents after corresponding IR heating treatments. The cooled samples were stored in polyethylene bags before they were further dried to 13.3±0.2% MC using room air. Two samples of each original weight of 250 g under each treatment were combined into one sample with a total weight more than 400 g for milling quality evaluation, which resulted in two samples under each treatment for the tests. The samples were stored in Ziplock bags at room temperature for about one month before milling.

Milling quality and evaluation
The most important rice milling quality indicators are total rice yield (TRY), head rice yield (HRY) and degree of milling. To evaluate the effect of different treatments, the rice samples of 400 g each were dehulled and milled by using Yamamoto Husker (FC-2K) and Yamamoto Rice Mill (VP-222N, Yamamoto Co. Ltd., Japan). The rice samples were milled three times to achieve the well milled rice as defined by the Federal Grain Inspection Service (USDA FGIS, 1994). For the first two times, the settings of Throughput and Whitening were 1 and 4, respectively. For the third time, the settings were 1 and 5. The evaluated milling quality indicators included TRY, HRY, and Whiteness Index (WI). The HRY was determined with Graincheck (Foss North America, Eden Prairie, MN). The WI was used to evaluate the whiteness (degree of milling) of milled rice and determined with the Whiteness Tester, C-300, (Kett Electronic Laboratory, Tokyo, Japan). High index number indicates whiter milled rice. All quality evaluations were conducted at Farmers' Rice Cooperative (West Sacramento, CA).
<u>Determine the effect of thickness of rice bed on heating and moisture removal rates and milling quality</u>

For this part of the study, the same procedures used for single-layer IR drying were also used. But the differences were the initial moisture contents of rough rice (23.8% and 20.6%) and rice bed thicknesses. Three rice bed thicknesses, single-layer, 5 mm and 10 mm were studied. The heating time also increased up to 120 s to achieve the required rice temperature. Based on the single-layer drying results, only natural cooling (slow cooling) was used after tempering because the force air cooling removed too much moisture to maintain high quality of milled rice.

SUMMARY OF 2006 RESEARCH (MAJOR ACCOMPLISHMENTS) BY OBJECTIVES:
<u>Study the heating and drying rates of rice in single-layer and moisture removal characteristics during cooling; Determine milling quality of IR dried rice</u>

Moisture removals under different heating durations

After the 20.6% and 25.0% MC rough rice samples were heated for 15, 40, 60, and 90 s, they reached corresponding temperatures of 42.8, 54.3, 61.2, 69.4°C, and 42.8, 55.5, 59.1, 68.0°C,

respectively. The low MC rice samples had slightly higher temperatures than the high MC rice samples at 60 and 90 s heating, which could be due to less energy used for heating the water and a lower evaporative cooling effect in the low MC rice than the high MC rice under the constant radiation heat supply. The maximum difference in temperatures of the samples with different original MC under the same heating duration was 2.2°C, which was relatively small. Therefore, the average temperatures of low and high MC rice samples at different heating durations are presented in Fig. 1. A high correlation between the average rice temperature and heating time was obtained with a power model. The model can be used to predict the temperature change for the rice with a known heating time under the tested moisture range and bed temperature. In our other experiments, the required heating time to reach a specific rice temperature was significantly reduced when the drying bed temperature increased by preheating to a higher temperature than the 35°C used in this study. If it is necessary to reduce the heating time, the method of preheating drying bed to a relatively high temperature could be considered. Further research is needed to study the effect of preheating temperature on the required heating time, moisture removal, and milling quality of rough rice.

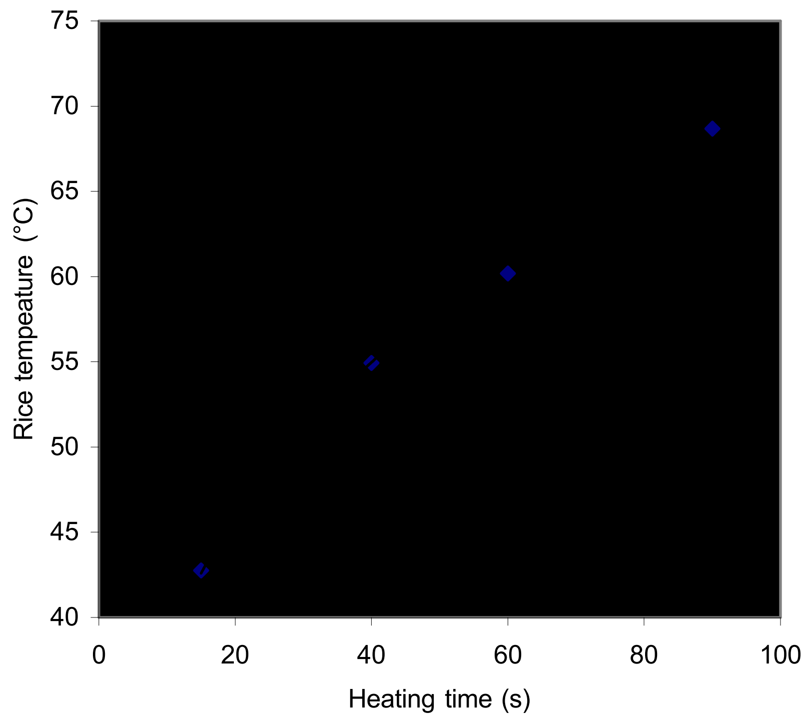

Fig. 1. Relationship between rice temperature and heating time

The trend of high moisture removal for the high MC rice samples was clearly shown in Fig. 2. even though the difference between the low and high moisture rice samples was relatively small. With 90 s heating (average temperature of 68.7°C), the moisture removal was 2.8 and 2.5 percentage points for the high and low MC rice samples. It is important to notice that the average drying rates of the rice samples with initial 25% and 20.5% MCs were 2.4, 1.8, 1.7, and 1.7 percentage points per minute at the moisture removal levels of 0.6, 1.2, 1.7, and 2.6 percentage points by each drying pass. The high drying rate at relative high moisture removal levels by each drying pass, for example of 1.7 percentage points per min at 1.7 and 2.6 percentage point MC removal, was much higher than that of current commercial, conventional heated air drying of 0.1 to 0.2 percentage points per min due to low heated air temperature used (Kunze and Calderwood, 1985). The high drying rate was achieved by using IR heating alone even without counting the moisture removal during cooling.

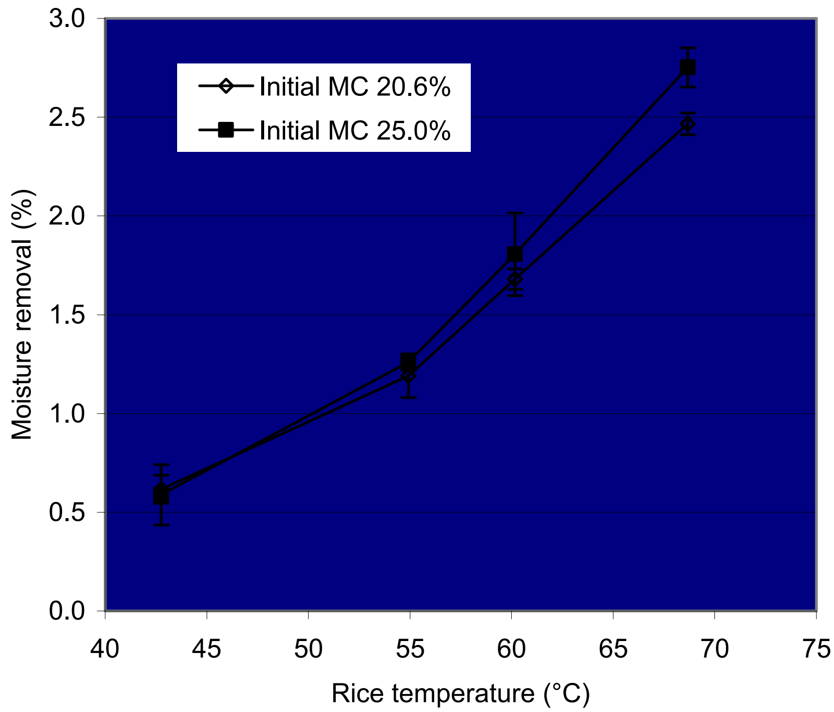

Fig. 2. Moisture removals of rice samples with different initial moisture contents after heated to various temperatures

Moisture removals under different tempering and cooling treatments

The clear trends of tempering vs. non-tempering and natural cooling vs. forced air cooling are seen in Figs. 3 and 4. For low MC rice, the moisture removals of tempered rice samples under natural cooling and forced air cooling were 0.6 to 1.3 and 1.1 to 1.9 percentage points, respectively, in the tested temperature range from 42.8°C to 69.4°C. In contrast, the non-tempering rice had 0.4 to 0.8 and 0.7 – 0.9 percentage point moisture removals under natural cooling and forced air cooling, respectively. The tempering resulted in 0.2 to 0.5 percentage point more MC removals than non-tempering, which showed that tempering treatment significantly improved the moisture removal during cooling compared to non-tempering samples. The forced air cooling also had more moisture removal up to 0.9 percentage points than natural cooling in the tested temperature range. However, at the high heating temperature of 69.4°C without tempering, similar moisture removals were achieved with both natural cooling and forced air cooling. This was due to the high moisture gradients after more than 2.5 percentage point moisture removal and moisture diffusion in the rice kernels became limited factor for further improving the drying rate by using increased drying force of forced air cooling.

The high MC rice had similar moisture removal trends as the low MC rice during cooling even though more moisture was removed compared to the low moisture rice. The tempered rice had the moisture removals of 1.6 to 2.2 percentage points for forced air cooling and 0.8 to 1.5 percentage points for natural cooling compared to 1.1 to 1.3 percentage points for forced air cooling and 0.4 to 1.1 percentage points for natural cooling of non-tempered rice in the tested temperature range. The tempering treatment resulted 0.4 to 0.5 and 0.5 to 0.9 percentage points more moisture removals than the non-tempering treatment under natural cooling and forced air cooling, respectively. The results indicate that tempering is even more important for high MC rice than low MC rice to have high MC removal during cooling.

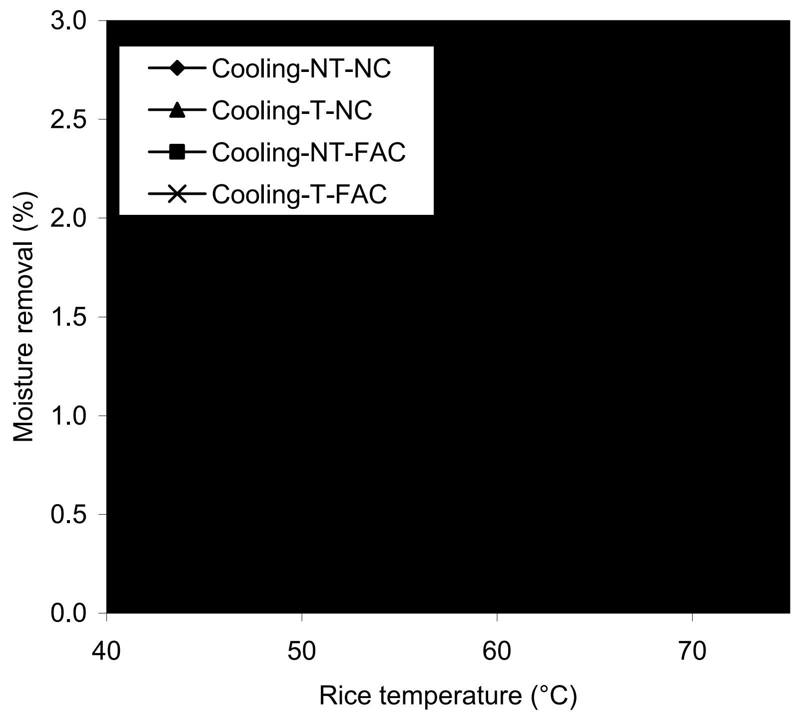

Fig. 3. Moisture removal of rice with initial MC of 20.6% under different cooling methods with and without tempering
(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

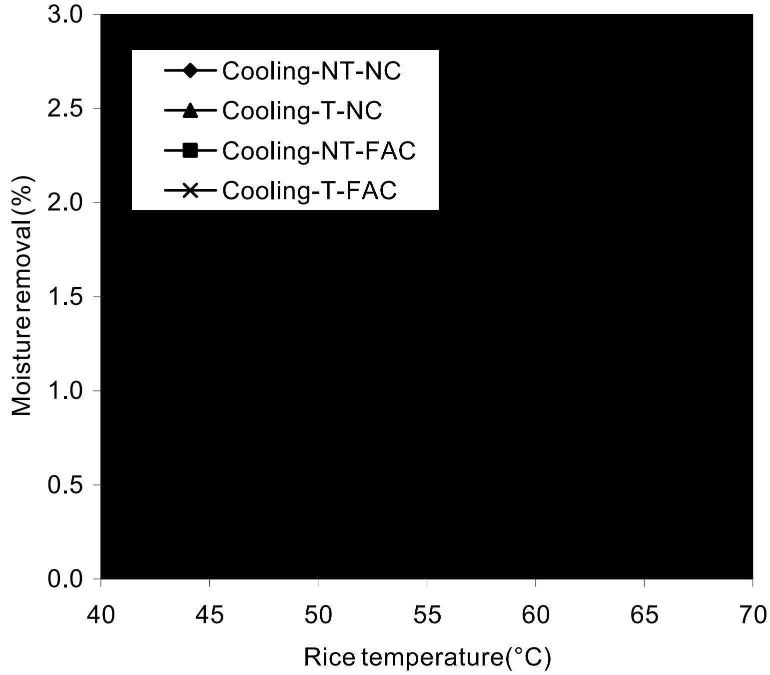

Fig. 4. Moisture removal of rice with initial MC of 25.0% under different cooling methods with and without tempering
(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

Based on the above results, the tempering process reduced the moisture gradient in rice kernels and allowed the moisture to equilibrate before the rice kernels were cooled. Without tempering, there was a significant moisture gradient in the rice kernels and low moisture content near the surface, which resulted in less moisture removal during cooling. In general, both reduced moisture gradient in the tempered rice kernels and forced air cooling increased the moisture removal during the cooling process. Therefore, the tempering process is a critical step to increase the moisture removal during cooling. In order to achieve high moisture removal during cooling, a combination of tempering and forced air cooling could be used even though the high moisture removal could cause rice fissures lowering rice milling quality which need to be considered.

The trend of total moisture removal at different temperatures with different tempering and cooling treatments was more or less parallel to the moisture removal caused by heating only (Figs. 5 and 6). The highest total MC removals of rice were 1.7 to 4.4 and 2.2 to 4.8 percentage points for low and high MC rice samples, respectively, which were achieved with tempering and forced air cooling among the treatments. But the lowest total MC removals were generally occurred for rice experienced non-tempering and natural cooling treatment. For rice treated with tempering and natural cooling, the total moisture removals were 1.4, 2.4, 3.2 and 4.3 percentage points for the high MC rice and 1.3, 2.0, 2.7 and 3.8 percentage points for the low MC rice under the tested temperature range. The moisture removals were the second highest among the treatments when the temperatures were above 55°C. These numbers indicated that 2.7 to 3.2 percentage point moisture were removed with 1 min heating followed by tempering and natural cooling. The drying rates were much higher than the 2 to 3 percentage point moisture removal with 15 to 20 min heating of the current conventional hot air drying.

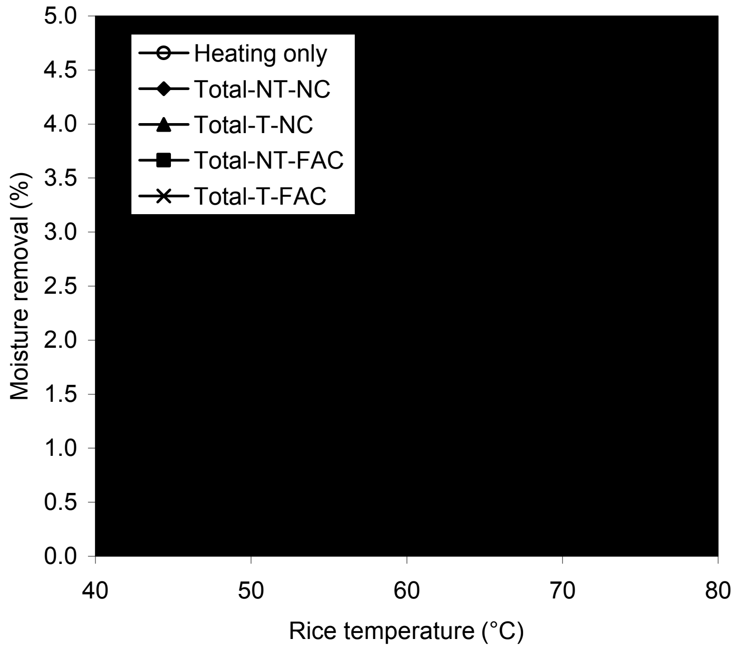

Fig. 5. Total moisture removal of rice with initial MC of 20.6% under different cooling methods with and without tempering
(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

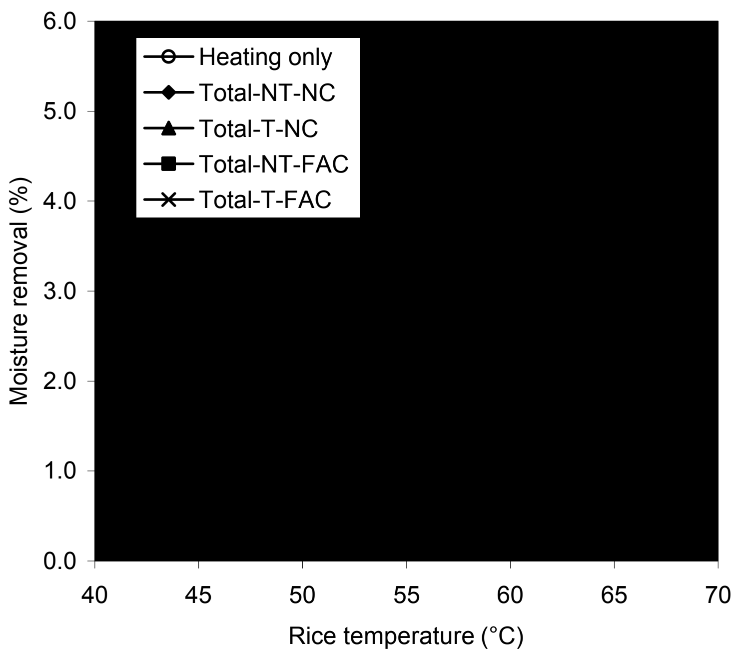

Fig. 6. Total moisture removal of rice with initial MC of 25.0% under different cooling methods with and without tempering
(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

For the total moisture removal, the moisture removed due to sensible heat during cooling was a very significant portion. For example, 37% and 44% of total moisture removals occurred during cooling when the low and high MC rice samples were heated for 60 s (about 60°C) followed by tempering and natural cooling. Because no additional heating energy is needed during the cooling, the high moisture removal could further improve the energy efficiency of the IR drying process. The exact amounts of energy saving and consumption still need to be determined in future research.

Milled rice quality

In general, for both the high and low initial moisture rice samples, infrared dried rice with tempering followed by natural cooling had similar and higher TRY compared to the control (Figs. 7 and 8). On average, the TRYs of low and high MC rice dried by using IR followed with natural cooling were 68.0% and 68.1%, respectively, which were 0.3 and 0.7 percentage points more than the controls. Especially, the rice dried at about 60°C with natural cooling had the highest TRYs of 68.4% for low moisture rice and 68.6% for high moisture rice compared to the controls of 67.7% and 67.4%, respectively. This meant that the TRYs of IR dried rough rice were 0.7 to 1.2 percentage points more than the control. However, the samples treated with other methods had much lower TRYs than the controls, especially for the rice with the low MC dried under the high temperature.

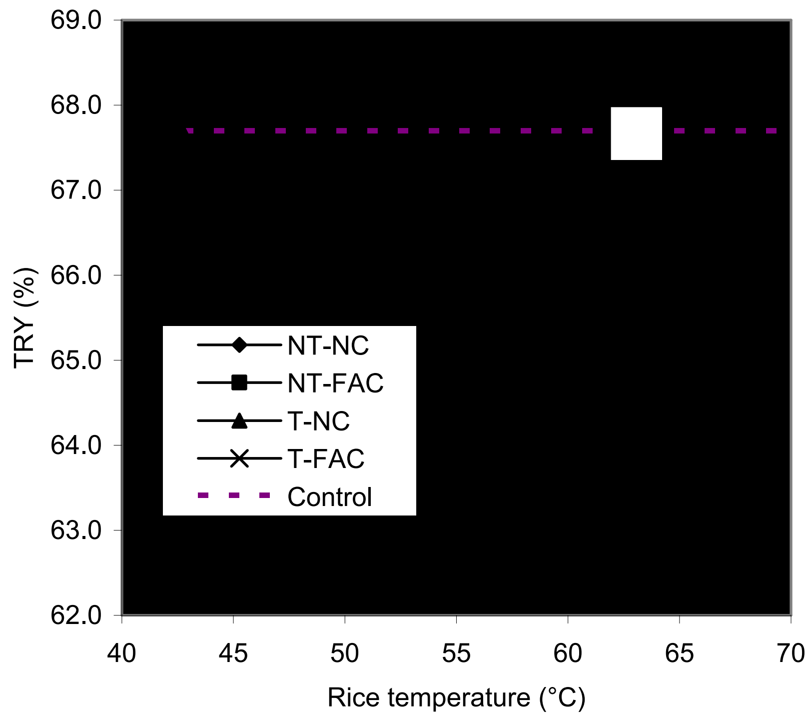

Fig. 7. Total rice yields of rice with 20.6% initial moisture content and different drying treatments
(T – Tempering, NT – No tempering, NC – Natural cooling, FAC – Forced air cooling)

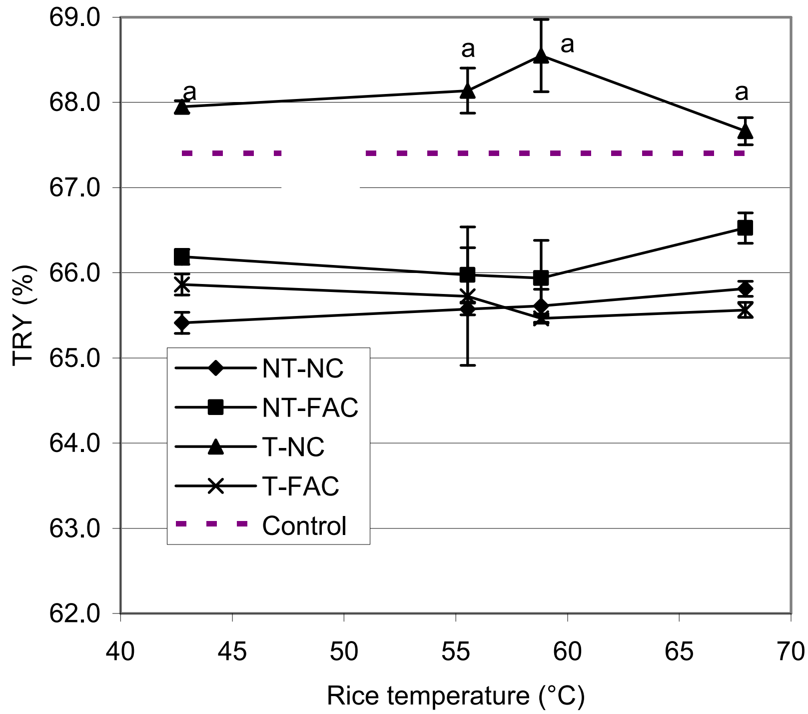

Fig. 8. Total rice yields of rice with 25.0% initial moisture content and different drying treatments

Similar trends were also observed for the HRYs (Figs. 9 and 10). The low MC rice samples dried using IR with tempering and natural cooling had significantly higher HRY (0.6 to 1.9 percentage points) than the control and the highest HRY of 65.2% was obtained with 61.2°C of rice temperature. For the high moisture rice, the rice dried followed by tempering and natural cooling had the same HRY (63.6%) at 58.8°C as the control and slightly lower HRY at 42.8°C and 55.5°C than the control. All other post heating treatments resulted in much lower HRYs.

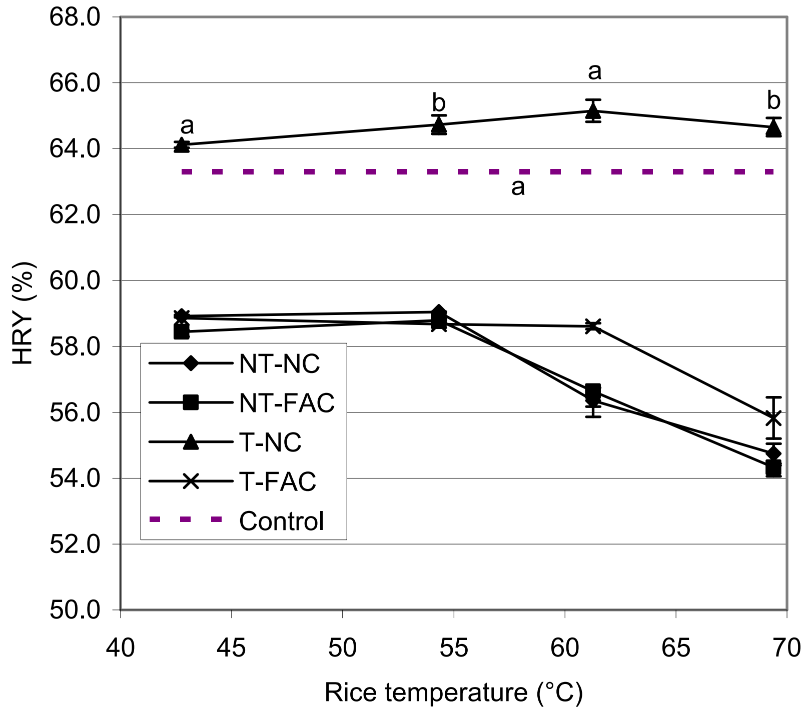

Fig. 9. Head rice yields of rice with 20.6% initial moisture content and different drying treatments

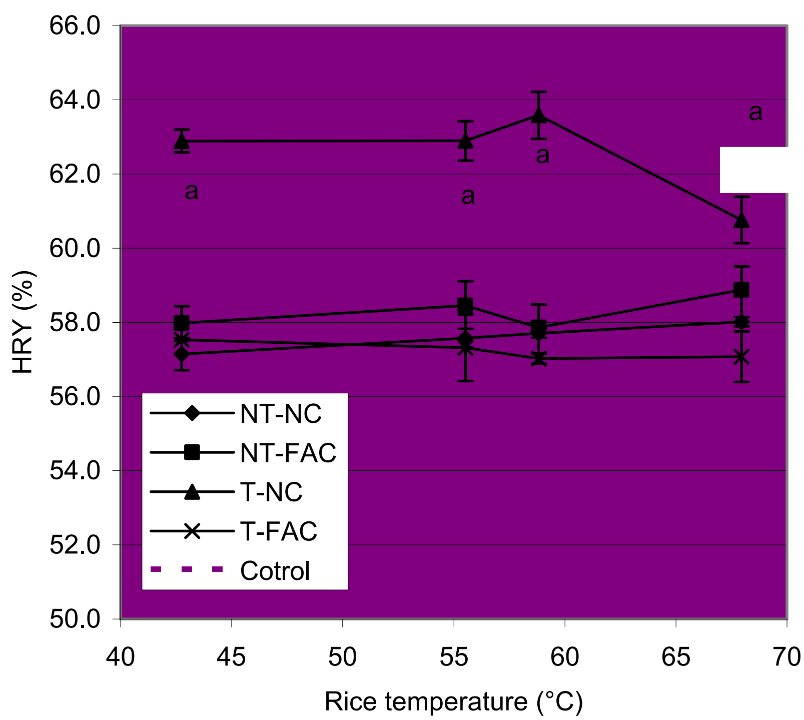

Fig. 10. Head rice yields of rice with 25.0% initial moisture content and different drying treatments

When the results of the WI of milled rice were examined, it can be seen that the IR dried rice generally had higher WI values than the controls, especially for the low MC rice, even though the differences between the controls and the some of the treated rice samples were not significant (Figs. 11 and 12). This indicated that most of IR dried rice with tempering followed by natural cooling had a similar milling degree to the control. It seems that there is the trend that WI increased with the increase of the rice drying temperature for the non-tempering treatment, especially for the low MC rice. This could be due to the difference in the hardness of rice with different treatments and/or the contribution of broken kernels to the color, which needs to be further studied.

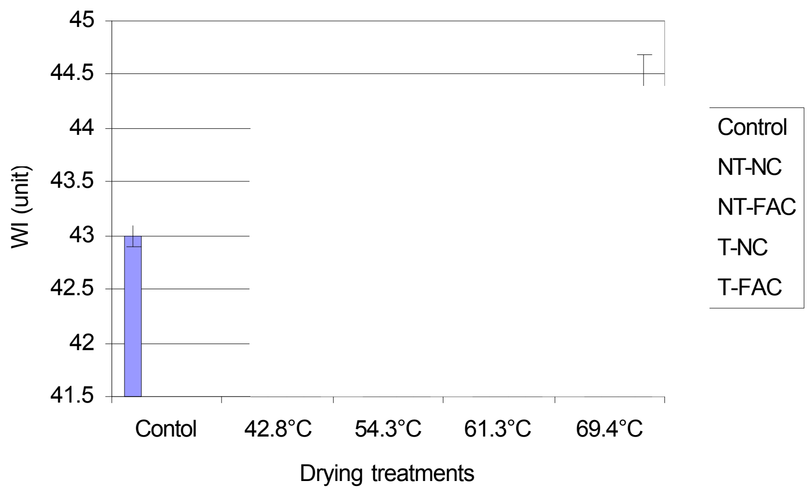

Fig. 11. Whiteness of milling rice with 20.6% initial moisture content and different drying treatments

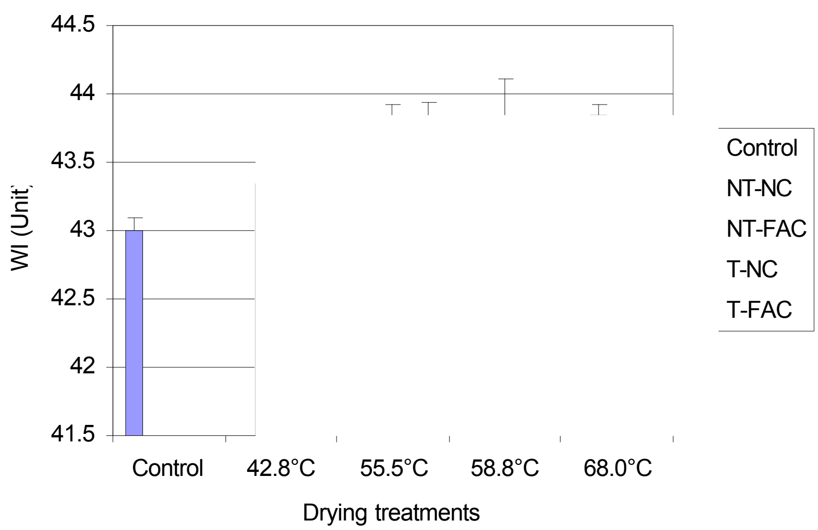

Fig. 12. Whiteness of milling of rice with 25.0% initial moisture content and different drying treatments

Based on the milling quality results, it can be concluded that rice can be dried by using IR followed by tempering and natural cooling to achieve superior rice milling quality. It is recommended that the rice temperature of IR heating is controlled at close or below 60°C. For the current rice drying practice, the drying temperature or heated air temperature is controlled away below the 60°C to avoid creating fissures lowering HRY. The reason that the high temperature of IR heating did not damage the rice quality could be due to the relative uniform heating in the rice kernel resulting from the IR penetration, which had less moisture gradient compared to conventional heated air drying. The results indicate rice milling quality may not be compromised with a relatively large amount of moisture removal in a single drying pass with high drying rate if the rice can be heated quickly and uniformly for minimizing the moisture gradient. When a large amount of moisture is removed during IR heating, tempering is very important to reestablish the moisture equilibrium in rice kernels.

This research also showed that the cooling method following the tempering was very important. The rapid cooling by using forced air can significantly lower the rice milling quality. Because a relative large amount of moisture was removed during forced air cooling, the cooling might regenerate significant moisture and temperature gradients causing fissures. Based on the glass transition hypothesis, the temperature and moisture at the rice surface were lowered first and starch reached glassy state during cooling. At the same time the center temperature and moisture of rice kernel were still relatively high and starch was remained at rubbery state. The differences in thermomechanical properties of starch at different stages would generate stress and fissure resulting in breakage in milling and lowered rice milling quality. Therefore, controlled slow cooling will be very important for high temperature rice drying. Since the natural cooling effectively preserved the quality, controlled slow cooling could be accomplished by low rates of air flow through a bin of rice to cause cooling.

<u>Determine the effect of thickness of rice bed on heating and moisture removal rates and milling quality</u>

Heating rates and moisture removals under different heating durations and bed-thicknesses

In general, the rice with high moisture content had slightly lower temperature at the same heating time compared to the low moisture rice as it has been observed above (Table 1). When the thickness of rice bed increased, the heating rate decreased. However, the decrease in the heating rate was not proportional. For example, the rice with 20.6% MC and three bed thicknesses, single-layer, 5 mm and 10 mm took 60, 90, and 120 s to reach 60-62°C. It can been seen that doubled thickness (from 5 to 10 mm) did not require doubled heating time to reach the temperature, which could increase the drying throughput compared to a thinner or single layer drying.

Table 1. Temperatures of rough rice after IR heating

Heating time	Original MC (23.8%)			Original MC (20.6%)		
(s)	Single-layer	5 mm	10 mm	Single-layer	5 mm	10 mm
15	42.4±0.3			42.6±0.6		
30		39.7±0.5	35.9±0.7		40.6±0.5	37.0±0.9
40	53.8±0.3			54.5±0.4		
60	60.6±0.6	50.6±0.7	48.4±0.9	61.8±0.8	53.4±0.4	46.2±0.6
90	67.5±0.6	59.1±0.7	52..3±1.0	69.4±0.9	60.2±0.6	53.4±1.0
120		70.5±0.7	60.3±0.5		71.4±0.8	61.2±0.9

The moisture removal was increased with the increased heating time or temperature as expected (Fig. 13). The rice with high original moisture had more moisture removal than the one with low moisture, especially at the high temperature range. When rice samples were heated to a similar temperature, the moisture removal during heating were similar, which indicated that the thickness was not the limiting factor for the moisture removal. It mainly depended on the rice temperature.

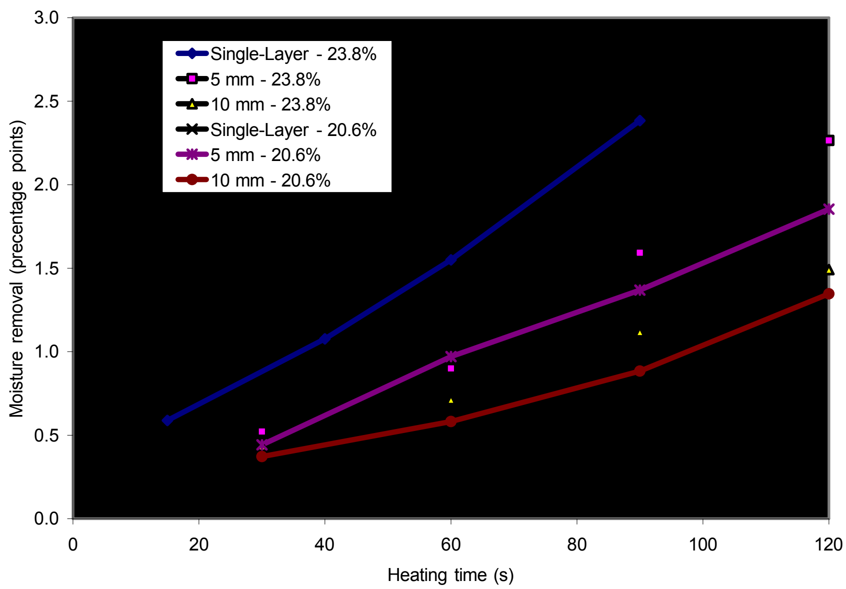

Fig. 13. Moisture removal of rice with different bed-thickness during heating

Similar the moisture removal during heating, the total moisture removals at a similar temperature were about the same for different bed thicknesses (Fig. 14). However, the total moisture removal of high moisture rice was much higher more than the low moisture rice. For example, when rice heat to about 60°C, the total moisture removals were 3.9% and 2.7% for high and low moisture rice, respectively.

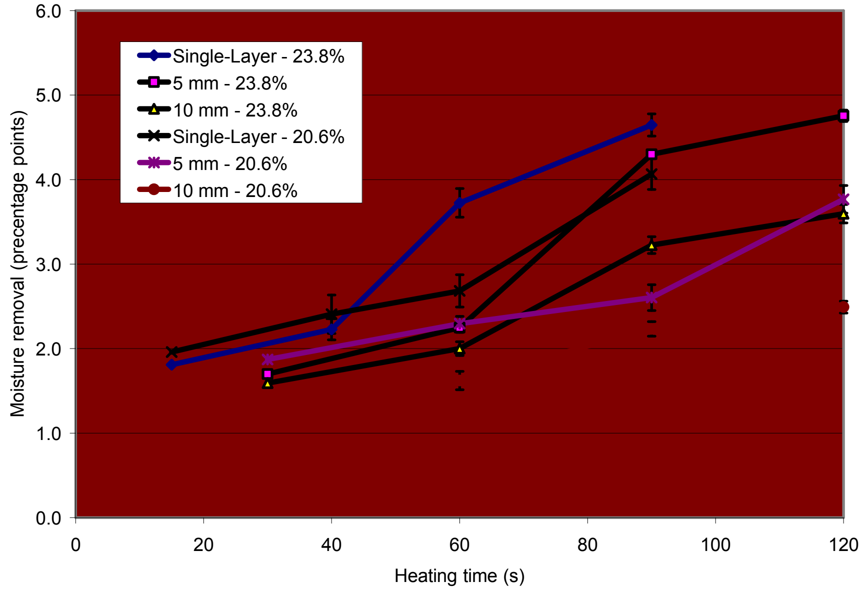

Fig. 14. Total moisture removal of rice with different bed thicknesses and treatments

Milling quality

When the milling quality was evaluated, it is very clear that heating rice samples to about 60°C resulting in higher TRY and HRY than the control (Figs. 15 and 16), which was similar to the results mentioned above . This indicated that high heating rate and milling quality can be achieved even for the rice bed thickness up to 10 mm which was maximum thickness studied in this research. There is a need to further research to study the effect of further increased bed thickness on drying and milling quality. All milled rice samples with different treatments has similar whiteness (data not shown).

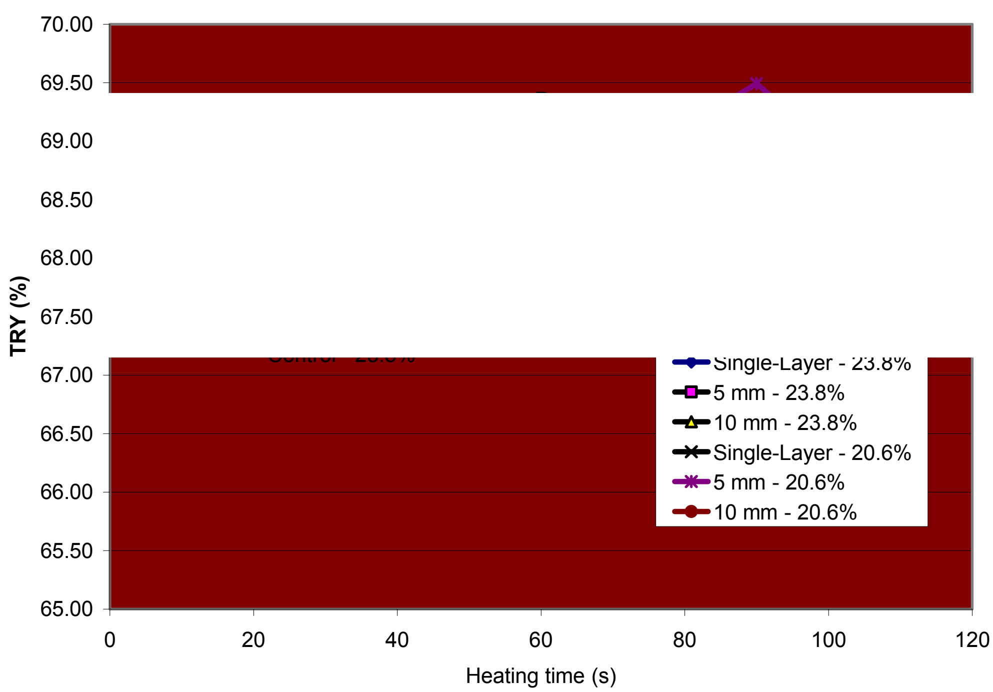

Fig. 15. Total rice yields of rice dried with different treatments

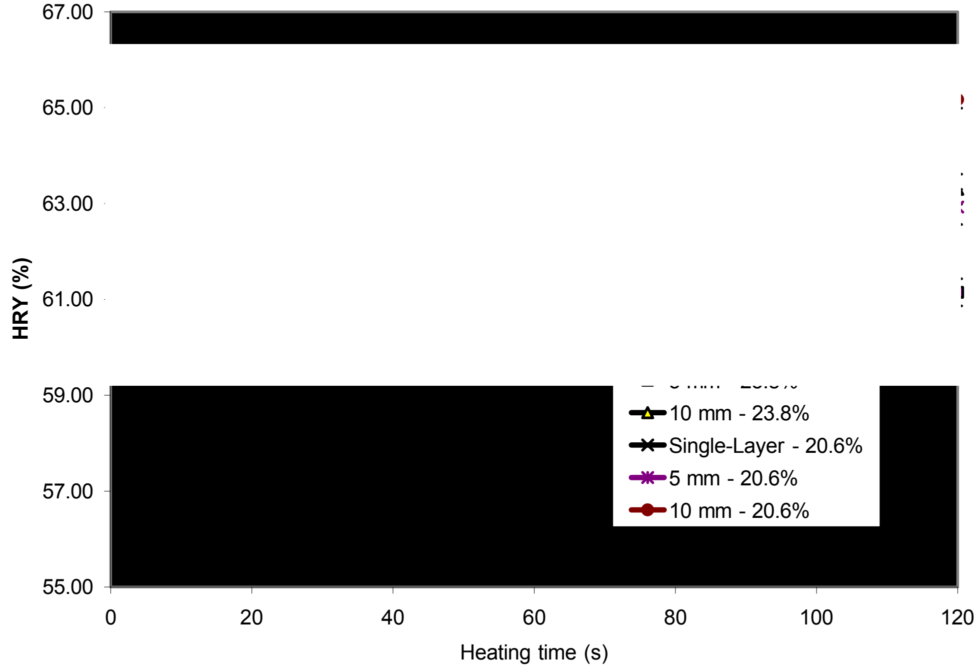

Fig. 16. Head rice yields of rice dried with different treatments

<u>Conclusions and recommendations</u>

The research showed high rice drying temperature can be achieved with a relatively short heating time by using catalytic IR emitter with single-layer or thin-layer of rough rice. The moisture removal during heating increased with an increase in rice temperature. It took only about 60, 90, and 120 s to achieved about 60°C rice temperature with for single-layer, 5 mm, and 10 mm bed thickness and removed 1.4 to 1.8 percentage point MC during IR heating alone depending upon the original MC. The total moisture removal after tempering and cooling was up to about 4 percentage points. The tempering process after the rapid IR heating and moisture removal is essential to achieve high rice milling quality and improve the amount of moisture removal during cooling. The natural (slow) cooling following the tempering treatment can be used to remove a significant amount of moisture with high rice milling quality. But the forced air cooling following heating or tempering could result in lowered rice milling quality, which is not recommended.

It is recommended to use IR heating to achieve high rice temperature (60°C) followed by tempering and slow cooling for improving rice milling quality with high drying rate. The total moisture removal in each drying and cooling pass could be in the range of 2.5% to 4% depending on the drying conditions and original moisture contents. The findings of this research could lead to new approaches of rice drying practice and rice dryer design.

PUBLICATIONS OR REPORTS:

N/A

CONCISE GENERAL SUMMARY OF CURRENT YEAR'S RESULTS:

The objectives of this research were to study the heating and moisture removal rates and quality characteristics of rough rice dried with infrared (IR) heating. The rice samples with different initial moisture contents from 20.6% to 25.0% (w.b) were dried with IR at a radiation intensity of 5348 W/m^2 under three different rice bed thicknesses, single-layer, 5 mm and 10 mm, for various times up to 120 s. The results showed that it took about 60, 90 and 120 s to achieve about 60°C of rice temperature for the rice with bed thicknesses of single-layer, 5 mm and 10 mm, respectively, which demonstrated the high heating rate of IR for rice drying.

The moisture removal during heating increased with the increase of rice temperature. It mainly depended on the rice temperature, not the thickness of rice bed. The tempering process after heating could significantly improve the removal during cooling step and milling quality. The cooling step also removed significant amount of moisture by slow cooling and forced air cooling. But the forced air cooling could reduce the milling quality due to too much moisture removed in the cooling step. All samples with slow cooling had high milling quality. It was also observed that all rice samples heated to about 60°C had higher milling quality compared to other treatment conditions including the control of ambient air drying, which could be related to thermomechanics of rice kernel and drying even though the exact reason was not known.

It is recommended to use IR heating to achieve high rice temperature (60°C) followed by tempering and slow cooling for improving rice milling quality with high drying rate. The total moisture removal in each drying and cooling pass could be in the range of 2.5% to 4% depending on the drying conditions and original moisture contents. The findings of this research could lead to new approaches of rice drying practice and rice dryer design.

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