MOISTURE REMOVAL CHARACTERISTICS OF THIN LAYER ROUGH RICE UNDER SEQUENCED INFRARED RADIATION HEATING AND COOLING

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ABSTRACT

The objective of this study was to investigate the moisture removal characteristics of thin layer rough rice heated by infrared (IR) and cooled with various cooling methods. Thin layer rough rice samples with different initial moisture contents (MCs) were heated using a catalytic IR emitter for four exposure times and radiation intensities. High heating rate and moisture removal were achieved during the IR heating period. After heating, more moisture removal was achieved during the cooling period. The achieved grain temperatures ranged from 35.1 to 68.4C under the tested heating conditions. The vacuum and forced air cooling methods removed more moisture than did the natural cooling. When rice with 25.7% MC was heated by IR, MC was reduced by 3.2, 3.5, and 3.8 percentage points for rice heated to 63.5C at the IR intensity of 5348 W/m^2 for120 s followed by natural cooling for 40 min, forced air cooling for 5 min and vacuum cooling for 10 min, respectively.

PRACTICAL APPLICATIONS

To design efficient infrared (IR) dryers for rough rice, it is important to optimize the operating parameters of IR dryer to achieve high heating rate, fast drying and good quality of end-products. To achieve the aforementioned objectives, we have been conducting several studies including our previous publications (Pan, Khir *et al.* and this study). The outcomes of our studies have clearly indicated that a high heating rate, fast drying, good quality and simultaneous drying and disinfestation can be achieved by IR heating of rough rice to bout 60C followed by tempering and natural cooling with tested bed thickness up to 10 mm. Consequently, IR heating followed by cooling could be an effective approach for designing IR rough rice dryers. It is expected that this alternative approach could be used as an energy saving drying method with improved drying efficiency, space saving, clean working environment and superior product quality compared with the conventional heated air drying method.

INTRODUCTION

Moisture content (MC) is one of the most important factors affecting the storage and subsequent handling processes, as well as the rice quality. Rough rice is normally harvested at an MC higher than the required level of 12–14% (wet basis) for safe storage. In order to reduce the MC to the safe storage level, rough rice is normally dried using convective heated air after harvest. However, heated air drying is a slow and energy intensive process that negatively impacts the economics of rice production.

Only relatively low temperature heated air is used in rice drying to avoid lowering the rice milling quality. When rough rice is dried with heated air, drying occurs through convection and conduction. The heated air warms the outer layer of the rice kernel first and causes the moisture to evaporate from the kernel surface. As more moisture is removed from the outer layers of the kernel, a moisture gradient is eventually established within the kernel. This gradient can induce tensile and compressive stresses resulting in endosperm fissures after cooling and lowering the head rice yield and milling quality (Ban 1971; Kunze and Choudhury 1972; Kunze 1979). Therefore, to minimize the moisture gradient generated during conventional rice drying, multiple drying passes are used in current drying practice. Rough rice is exposed to relatively low temperature air (up to 54C for 15–20 min) to remove a relatively small amount of moisture (2–3%) in each drying pass (Kunze and Calderwood 1985). For commercial drying, the temperature is usually much lower than 54C. The prolonged drying process due to the low drying temperature has low energy efficiency and may still cause some loss in the head rice yield and milling quality. It would be useful to develop a drying method that can shorten the drying time and reduce energy consumption while maintaining rice yield and milling quality.

Infrared (IR) radiation has received considerable attention lately because of its advantages in shortening drying time, high energy transfer rate and superior product quality compared with conventional heated air drying (Afzal *et al.* 1999; Tan *et al.* 2001; Pan *et al.* 2008b; Shih *et al.* 2008). It could be used as an energy saving drying method with improved drying efficiency, space saving and clean working environment (Ratti and Mujumdar 1995). When used to heat or dry moist materials, IR radiation impinges on the exposed material and penetrates it, and then the radiation energy is converted into heat (Ginzburg 1969). The penetration could provide more uniform heating in the rice kernel and may reduce the moisture gradient during heating and drying, thereby maintaining yield and milling quality (Pan *et al.* 2011). Also, because IR does not heat up the surrounding medium, the temperature of the rice kernel is not limited by the wet bulb temperature of the air, and the rice kernel can be quickly heated to high temperatures. The direct application of IR energy for a short time followed by cooling may have considerable prospect for increasing the drying rate. The increased temperature of rice kernel caused by the IR heating results in the increased vapor pressure in the grain, which promotes the migration of moisture to the surface of grain. Then the moisture can be removed by ventilating air during cooling. Sattish *et al.* (1970) summarized some advantages of using IR to preheat grains for drying, which include (1) high rate of heat transfer; (2) efficient transmission through the air or evacuated space; (3) cleanliness; (4) compactness of equipment; and (5) ease of automation.

It has been reported that high rice drying rate was achieved by spreading the rice in a single or a thin layer when using IR for drying rough rice (Pan *et al.* 2008a; Khir *et al.* 2011). Also, when IR was used to preheat rough rice to 60C followed by 49C heated air drying for 2–3 min, approximately 2% MC was removed by each pass (Schroeder and Rosberg 1960; Schroeder 1960, 1961; Hall 1962). Rao (1983) reported that it took only 7 min to reduce the MC from 20 to 14.8% (d.b.) using near IR heating compared with 30 min used for hot air drying. In addition, Bekki (1991) found that the maximum absorption of IR radiation by medium grain rough rice occurred at a wavelength of 2.9 μm. The maximum depth of penetration into agricultural produce has been found to be 18 mm (Ginzburg 1969; Sandu 1986). Thus, the application of IR heating for achieving high drying rate should be focused on thin layer drying. Pan *et al.* (2008a) found that high heating and drying rate can be achieved by using IR to heat rough rice as a single layer. Also, IR heating resulted in simultaneous drying and disinfestation without any adverse effect on milling quality.

Vacuum cooling is a relatively rapid cooling method for porous and moist foods and agricultural products. IR heating followed by vacuum cooling to perform a drying operation is based on the following considerations. IR is capable of rapidly and homogeneously heating products with small dimensions. Vacuum enhances moisture transfer because of an increased pressure gradient between the inside and the outside of the product. Also, the vacuum lowers the boiling point of water, increasing the evaporation rate. Removing water requires energy, which comes from the sensible heat of the product (Rennie *et al.* 2001; Wang and Sun 2001). The advantages of vacuum cooling include shortened time, extended product shelf life and improved product quality and safety, which have been demonstrated by the food industry. Vacuum-cooled products are also found to have a much more uniform internal temperature distribution as compared with the products cooled using conventional cooling methods (Mongpraneet *et al.* 2002; Zheng and Sun 2004).

Our previous studies have clearly indicated that a high heating rate, fast drying, good quality and simultaneous drying and disinfestation can be achieved by IR heating of rough rice to about 60C followed by tempering and natural cooling with tested bed thickness up to 10 mm (Pan *et al.* 2008a, 2011; Khir *et al.* 2011). As IR can be used to heat a thin layer of rough rice quickly to a relatively high temperature, it is possible to use the sensible heat from the rice to remove more moisture during cooling. IR heating followed by cooling could improve rice drying rate and total moisture removal in each drying pass and make IR drying more energy efficient. In addition, it is essential to study the effects of operating parameters of the IR dryer on rough

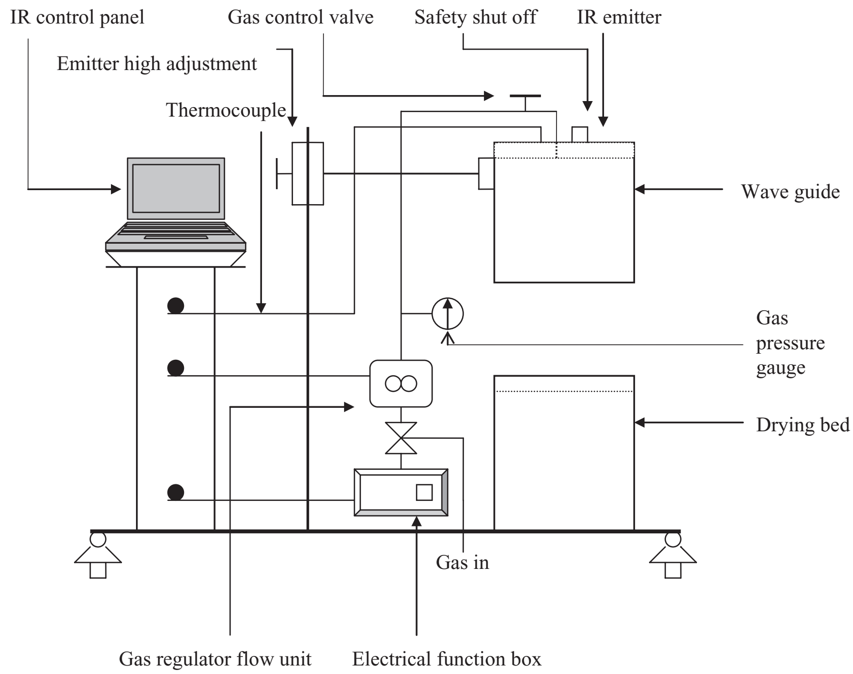

FIG. 1. SCHEMATIC DIAGRAM OF THE INFRARED DRYER SETUP

rice drying characteristics. However, no previous studies are available on these aspects. Therefore, the objectives of this research were (1) to study the effects of operating parameters of the IR dryer, including radiation intensity, heating time and initial MC, on grain temperatures and moisture removal of thin layer rough rice; (2) to investigate the effectiveness of various cooling methods, including natural cooling, forced air cooling and vacuum cooling, for removing additional moisture after IR heating; and (3) to develop regression models for predicting rice temperatures and moisture removals based on the operating parameters.

MATERIALS AND METHODS

IR Drying Device

A laboratory scale IR dryer was developed in the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis, as shown in Fig. 1. The IR dryer was composed of two main components: IR emitter and drying bed. A catalytic emitter provided by Catalytic Industrial Group (Independence, KS) 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 dimensions of the emitter were 30×60 cm, and it had a surface temperature of approximately 650C with corresponding peak wavelength of 3.1 μm, assuming the emitter is a black body. An aluminum box with dimensions of 65 cm (length) × 37 cm (width) × 45 cm (height) was installed around the emitter as a wave guide to achieve uniform IR intensity at the rice bed surface. The dimensions of the drying bed, constructed of aluminum plate of 3 mm thickness, were 65 cm (working length) × 36 cm (width) × 3 cm (depth). Aluminum was selected as its high reflectivity minimized the radiation energy loss through the drying bed. The reflected radiation also heated the bottom side of the rice kernels. A piece of plywood was installed beneath the aluminum plate to reduce conduction losses. Two type-T thermocouples (time constant of 0.15 s) were embedded on the bed surface to measure the bed temperature. The rice bed was located at 5, 10, 15 and 20 cm below the bottom edge of the wave guide with corresponding average IR intensities of 3,616, 4,023, 4,685 and 5,348 W/m^2 at the rice bed surface. The radiation intensity was measured with an Ophir FL205A Thermal Excimer Absorber Head (Ophir, Washington, MA).

Rewetting Procedures

Medium grain rice, variety M202, with MC of 11.0 ± 0.3% (wb) obtained from Pacific International Rice Mills, Inc. (Woodland, CA), was used for this study. The rice samples with high initial MCs were prepared by rewetting the rough rice for 48 h then aerating for 1 h to remove free moisture clinging to the grain surface. The amount of water added to the dry rice was calculated based on the sample weight and initial MC to reach the target MCs. The rewetted rough samples were placed in Ziplock bags and stored at 4C. After 1 week of storage, the samples were allowed sufficient time (about 3 h) to reach equilibrium at room temperature before the drying tests. Before the drying test, the MCs of the samples were determined by the air oven method (130C for 24 h) (ASAE 1995) and all reported MCs are on wet basis. The initial MCs of the samples were 16.7 ± 0.2%, 20.5 ± 0.3%, 23.6 ± 0.3% and 25.7 ± 0.2%.

Drying Procedures

Two replications of a full factorial experimental design with the four initial MCs, four IR radiation intensities (3,616, 4,023, 4,685 and 5,348 W/m^2) and four heating time durations (30, 60, 90 and 120 s) resulted in 128 total observations. The radiation intensities were selected based on targeted temperatures ranging from 35 to 70C. For each drying test, a 600 g rice sample was placed on the drying bed as a thin layer of 10 ± 2 mm with loading rate of 5.3 kg/m^2. The initial drying bed temperature was 35C.

Cooling Procedures

Three cooling methods – natural (slow) cooling, forced air cooling and vacuum cooling – were tested. After IR heating, each sample was divided into thirds. Each of these subsamples was weighed, then placed on a cooling bed as a thin layer of 10 ± 2 mm. The temperatures of the samples were measured at the beginning and end of the cooling process, and the samples were reweighed after cooling. The cooling times were 20–40, 5 and 10 min for natural cooling, forced air cooling and vacuum cooling, respectively. At the end of cooling, the sample temperature was close to the room temperature. The natural and forced air cooling treatments used ambient air; the air velocity for forced cooling was 0.1 m/s, similar to that used in commercial drying. The vacuum cooling was conducted by placing the samples in a vacuum oven (THELCO, Chicago, IL) set at room temperature and a pressure of 98.2 kPa. The moisture removal during cooling was calculated as the difference between the MC after IR heating and the MC after cooling and reported as percentage points.

Rice temperature and weight were measured at the end of each heating period. After heating, the rice temperature was measured using a Type-T thermocouple (time constant of 0.15 s, Omega Engineering, Inc., Stamford, CT) immediately after the rice was collected into a preheated container with the targeted rice temperature (Pan *et al.* 2008a). The thermocouple was kept at the center of rice mass until the temperature reading stabilized, which normally took from 10 to 30 s. The average temperature of the two replicates for each treatment is reported. The rice sample weights were measured via a balance with two-decimal accuracy before and after heating. The weight loss during heating and the initial MC were used to calculate the moisture removal during the heating period. The moisture removals in the tables and figures reported as percentage points were calculated as the differences between the initial MCs and the corresponding MCs after treatment.

Development of Regression Models

In order to accurately predict the rice temperatures and moisture removals under various operating conditions, which is important in the design of drying systems, multiple linear regression models were devolved. The Sigma Stat software (version 2.0, Jandel Corporation, San Rafael, CA) was used to develop models between dependent and independent variables. Dependent variables included rice temperatures and moisture removals. Independent variables included heating time, radiation intensity and initial MC.

RESULTS AND DISCUSSION

Rice Temperature

The temperatures of heated rice samples ranged from 35.1 to 68.4C under the tested conditions. Temperature increased with the increase of heating time and radiation intensity for samples with the same initial MC and decreased slightly with the increase of initial MC. For example, the temperatures of heated rice increased from 36.5, 36.3, 36.0 and 35.1C to 68.4, 66.5, 64.7 and 63.5C by increasing heating time from 30 to 120 s and radiation intensity from 3,616 to 5,348 W/m^2 for rice samples with initial MCs of 16.7, 20.5, 23.6 and 25.7%, respectively. The low MC rice had slightly higher temperatures than the high MC rice, especially, at 90 and 120 s heating, which could be due to less energy used for heating the water in the low MC rice than the high MC rice under the constant radiation heat supply. Temperatures for different heating times, initial MCs and radiation intensities are presented in Fig. 2. The average differences were 1.7 ± 0.5, 3.2 ± 0.6, 1.6 ± 0.6, 2.6 ± 0.6 and 1 ± 0.2C between the samples with MCs of 16.7 and 20.5%, 16.7 and 23.6%, 20.5 and 23.6%, 20.5 and 25.7%, and 23.6 and 25.7%, respectively. The maximum difference in the temperatures with same radiation intensity (5,348 W/m^2) was 4.3 ± 0.7C between the low MC rice (16.7%) and high MC rice (25.7%) at the heating time of 120 s. The results indicated that the effect of initial MC on rice temperature was relatively small compared with IR intensity and heating time. Moreover, high rice temperature can be achieved during a short time period using IR heating. This is in agreement with results of the previous studies (Khir *et al.* 2011; Pan *et al.* 2008a). We developed the following linear regression model to predict temperature

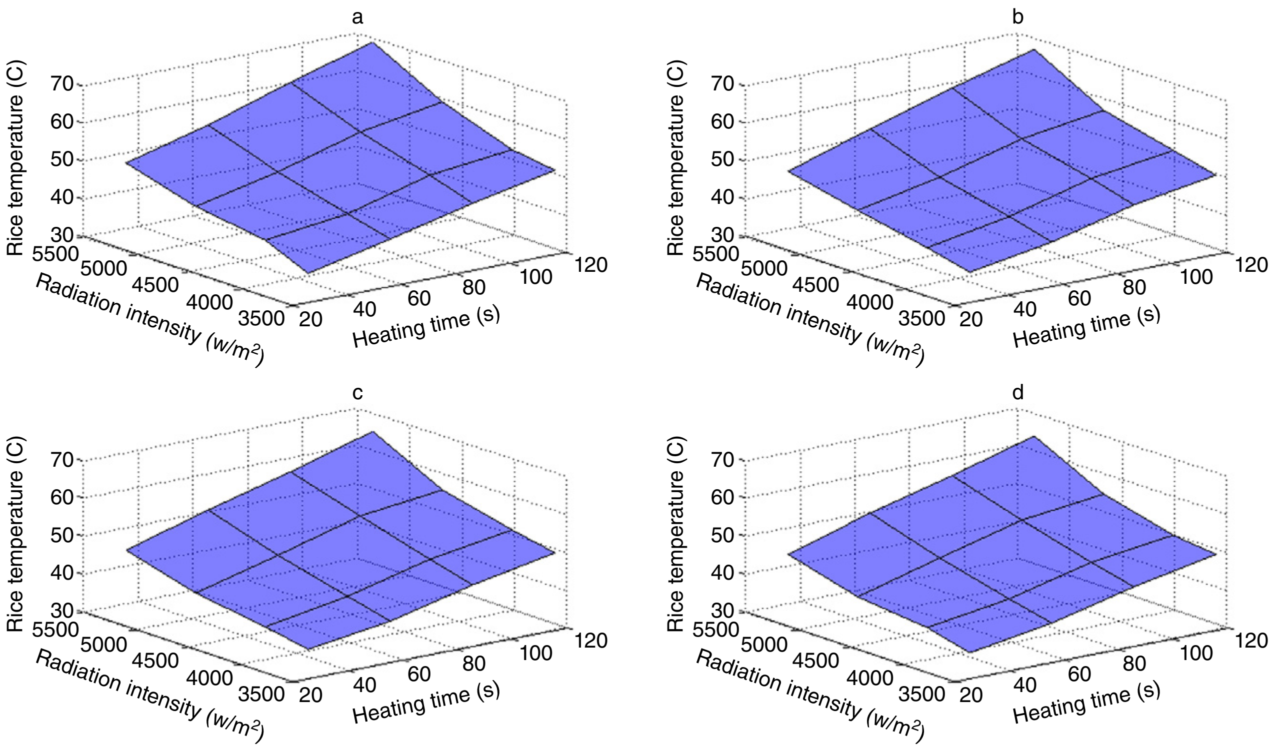

FIG. 2. RICE GRAIN TEMPERATURES UNDER DIFFERENT HEATING TIME PERIODS AND RADIATION INTENSITIES AT INITIAL MOISTURE CONTENTS OF (A) 16.7, (B) 20.5, (C) 23.6 AND (D) 25.7%

change as a function of heating time, t (s), radiation intensity, I (W/m^2), and initial MC, M (% wb):

$$Rice\ temperature(T) = 8.424 + 0.166 * t + 0.00792 * I - 0.344 * M \quad r^2 = 0.975$$

Figure 3 displays the observed and predicted rice temperature values over the ranges of heating time and radiation intensity at initial MC mean for each combination of heating time and radiation intensity. The differences between calculated rice grain temperatures using themod-

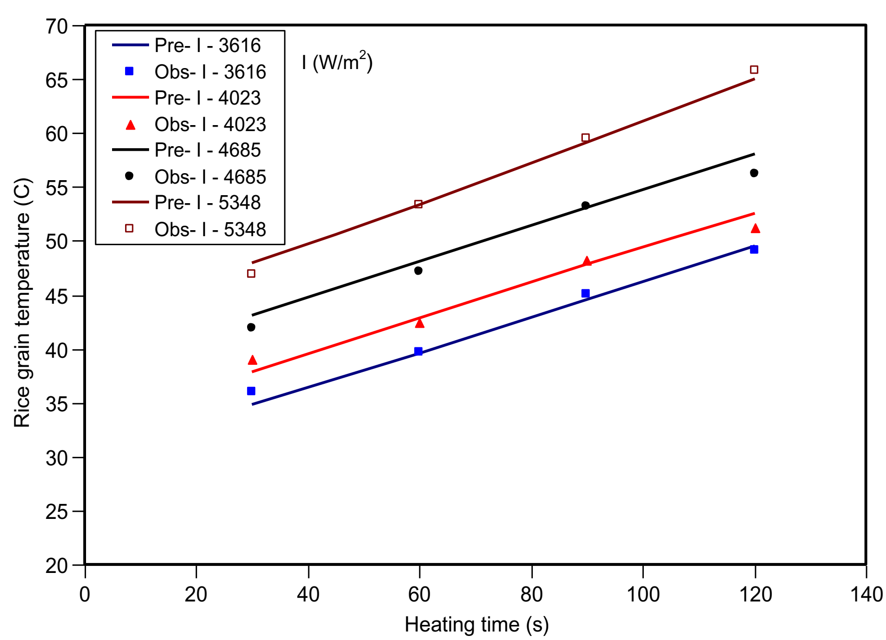

FIG. 3. OBSERVED AND PREDICATED RICE GRAIN TEMPERATURES OVER RANGES OF HEATING TIME AND RADIATION INTENSITY

TABLE 1. DIFFERENCES BETWEEN MEASURED AND CALCULATED RICE GRAIN TEMPERATURES DURING INFRARED HEATING UNDER DIFFERENT RADIATION INTENSITIES, HEATING TIMES AND INITIAL MOISTURE CONTENTS

Radiation intensity (W/m^2)	Heating time(s)	Initial moisture content (%)			
		16.7	20.5	23.6	25.7
3,616	30	0.2	1.3	1.1	0.9
	60	−0.5	0	0.3	0.5
	90	−0.3	0.6	0.6	0.8
	120	−0.7	−0.7	−0.2	0.2
4,023	30	1.5	0.8	1.1	1.6
	60	−0.8	−0.2	−0.1	−0.1
	90	0.2	0.6	0.4	0.3
	120	−1.3	−1.2	−1.1	−1.8
4,685	30	−1	−0.7	−1.4	−1.7
	60	−1	−1.1	−0.7	−0.6
	90	0.3	−0.2	0.4	0.1
	120	−1	−1.9	−1.9	−2.3
5,348	30	−0.8	−1.7	−1.4	−1.8
	60	0	0.3	−0.1	−0.2
	90	2	1.8	0.7	0.4
	120	1.4	0.9	2.1	0.6

eland measured rice grain temperatures under various conditions are presented in Table 1. The maximum difference was 2.3C, which was relatively small.

Moisture Removal during IR Heating

The results of moisture removals for rice samples with different initial MCs, heating times and radiation intensities are shown in Fig. 4. It is apparent that the rice moisture removal increased with the increased heating time under specific radiation intensity and initial MC, as would be anticipated due to additional energy absorption and therefore greater evaporation. The results also clearly showed that more moisture was removed from rice with high initial MCs. The moisture removals varied from 0.2 to 0.6 percentage points at the initial MCs of 16.7–25.7% for the rice samples heated for 30 s under radiation intensity of 3,616 W/m^2. Also, the moisture removals varied from 1.5 to 2.5 percentage points at the initial MCs of 16.7–25.7% for the rice samples heated for 120 s under radiation intensity of 5,348 W/m^2. The moisture removal results were similar to those reported by Faulkner and Wratten (1966, 1970). A multiple linear regression model to predict moisture removal was obtained, with independent variables of heating time, t (s), radiation intensity, I (W/m^2), and initial MC, M (% wb).

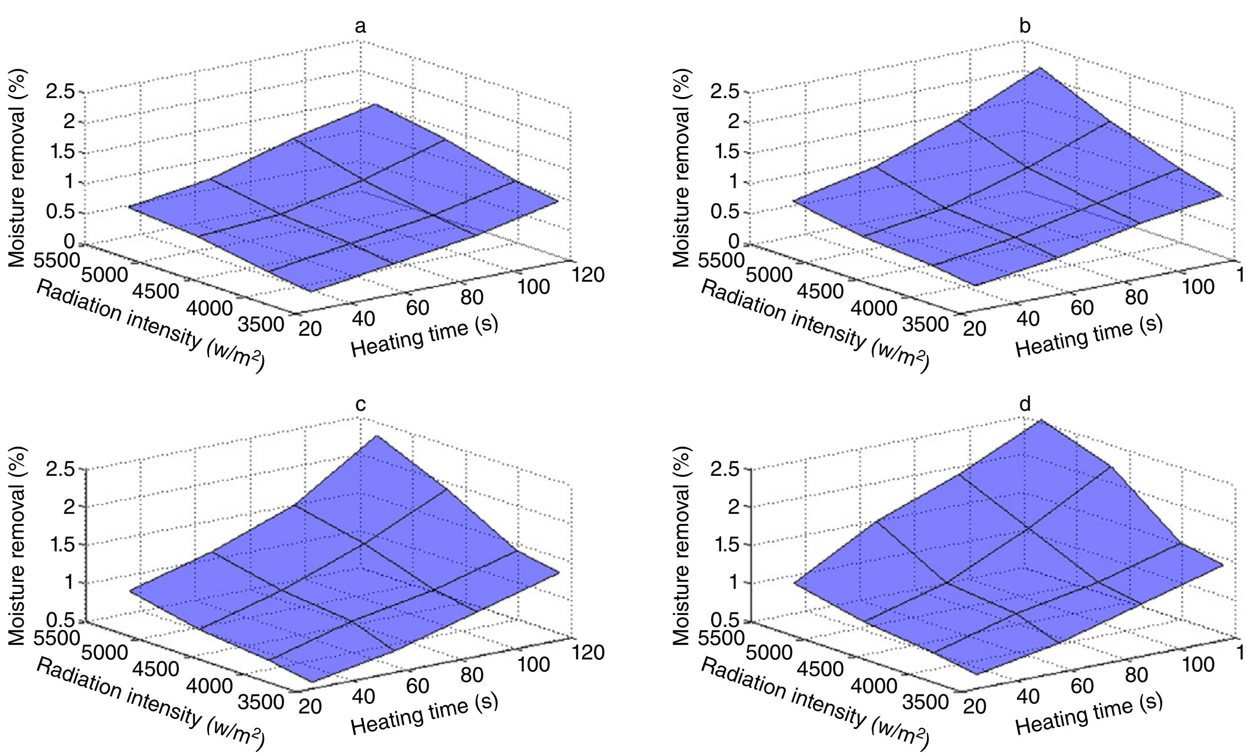

FIG. 4. MOISTURE REMOVAL UNDER DIFFERENT HEATING TIMES AND RADIATION INTENSITIES AT INITIAL MOISTURE CONTENTS OF (A) 16.7, (B) 20.5, (C) 23.6 AND (D) 25.7%

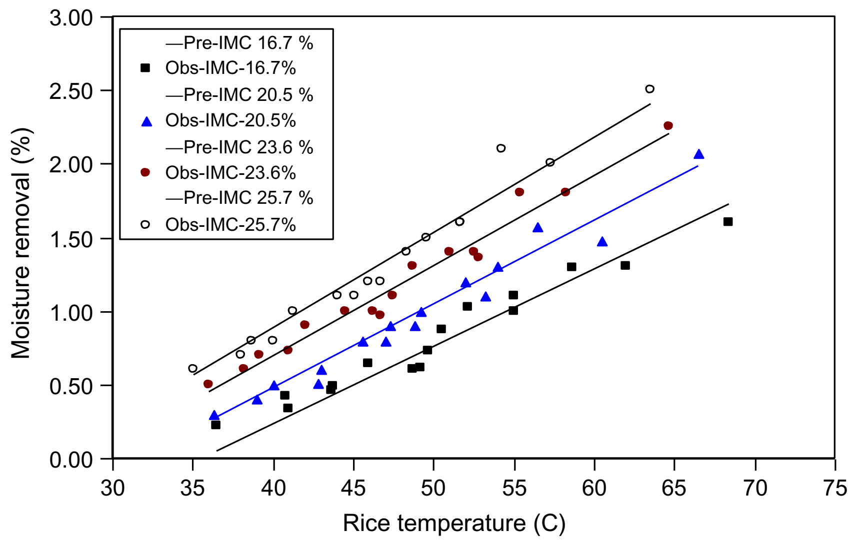

FIG. 5. OBSERVED AND PREDICTED MOISTURE REMOVALS FOR DIFFERENT INITIAL MCs AT RICE TEMPERATURES ACHIEVED OVER RANGES OF HEATING TIME AND RADIATION INTENSITY

$$\textit{Moisture removal MR}(\%) = -2.814 + 0.0109 * t + 0.000377 * I + 0.0634 * M \quad r^2 = 0.93$$

Figure 5 displays the observed and predicted moisture removals for different initial MCs at rice temperatures achieved over ranges of heating time and radiation intensity. The differences between calculated moisture removals using this model and measured moisture removals are presented in Table 2. There was no significant difference at ($P < 0.05$) between calculated and measured moisture removals.

Figure 6 displays the relationship between the radiation intensity and average drying rate with different initial MCs. It is important to note that the drying rate decreased as the initial MC of the rice decreased, but it increased with the increase of radiation intensity. The observed drying rates ranged from 0.4 to 1.5 percentage points per minute, substantially higher than the rates of 0.1–0.2 points per minute achieved with current commercial, conventional heated air drying (Kunze and Calderwood 1985).

Moisture Removals with Different Cooling Methods

The moisture removal results of rice samples with different initial MCs and cooling methods are shown in Fig. 7. In general, the vacuum cooling removed the largest amount of moisture, followed by forced air cooling and natural cooling, other conditions being equal. The average moisture removals by vacuum cooling, forced air cooling and natural cooling were 0.3, 0.4, and 0.5 percentage points for rice heated with radiation intensity 3,616 w/m^2 and similarly 0.57, 0.6 and 0.7 percentage points with radiation intensity 5,348 w/m^2 for the low moisture rice (16.7%), which compared with 0.6, 0.7 and 0.8 percentage points with radiation of 3,616 w/m^2 and 0.64, 1.0 and 1.1 percentage points with radiation intensity of 5,348 w/m^2 for the high moisture rice (25.7%), correspondingly. The vacuum cooling had moisture removal up to 0.5 percentage points more than natural cooling and 0.2 percentage points more than forced air cooling for the rice with the highest initial MC and processed with the high temperature.

TABLE 2. DIFFERENCE BETWEEN MEASURED AND CALCULATED MOISTURE REMOVAL DURING INFRARED HEATING UNDER DIFFERENT HEATING TIMES, RADIATION INTENSITIES AND INITIAL MOISTURE CONTENTS

Radiation intensity (W/m^2)	Heating time (s)	Initial moisture content (%)			
		16.7	20.5	23.6	25.7
3,616	30	0.1	0.1	0.1	0.1
	60	0.1	0	0	0
	90	0	0	0	−0.1
	120	0	−0.2	−0.1	−0.1
4,023	30	0.2	0.1	0.1	0
	60	0.1	−0.1	0	0
	90	0	−0.1	−0.1	−0.1
	120	−0.1	−0.1	−0.1	−0.1
4,685	30	0.2	−0.1	−0.1	−0.1
	60	−0.1	−0.2	−0.1	−0.1
	90	−0.1	−0.1	0	0
	120	0	0	0.1	0.2
5,348	30	0	−0.1	−0.1	−0.2
	60	−0.1	−0.2	−0.2	0.1
	90	0	0	−0.1	0.2
	120	−0.1	0.2	0.2	0.2

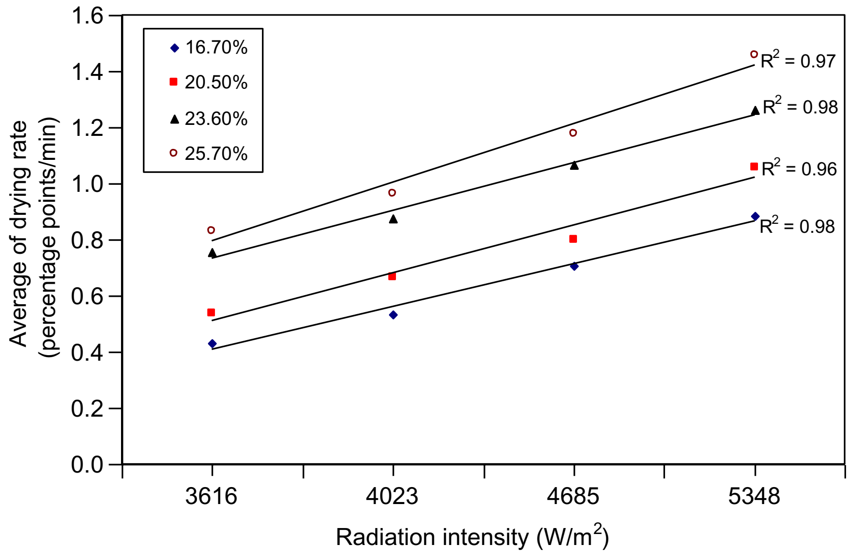

FIG. 6. RELATIONSHIP BETWEEN RADIATION INTENSITY AND DRYING RATE AVERAGE WITH DIFFERENT INITIAL MCs

Total Moisture Removals

The total moisture removal results from IR heating and cooling had a parallel trend between the moisture removal and heating time for the different cooling methods (Table 3). When the radiation intensity was 5,348 w/m^2 and heating time was 120 s followed by natural cooling, forced air cooling and vacuum cooling, the highest corresponding

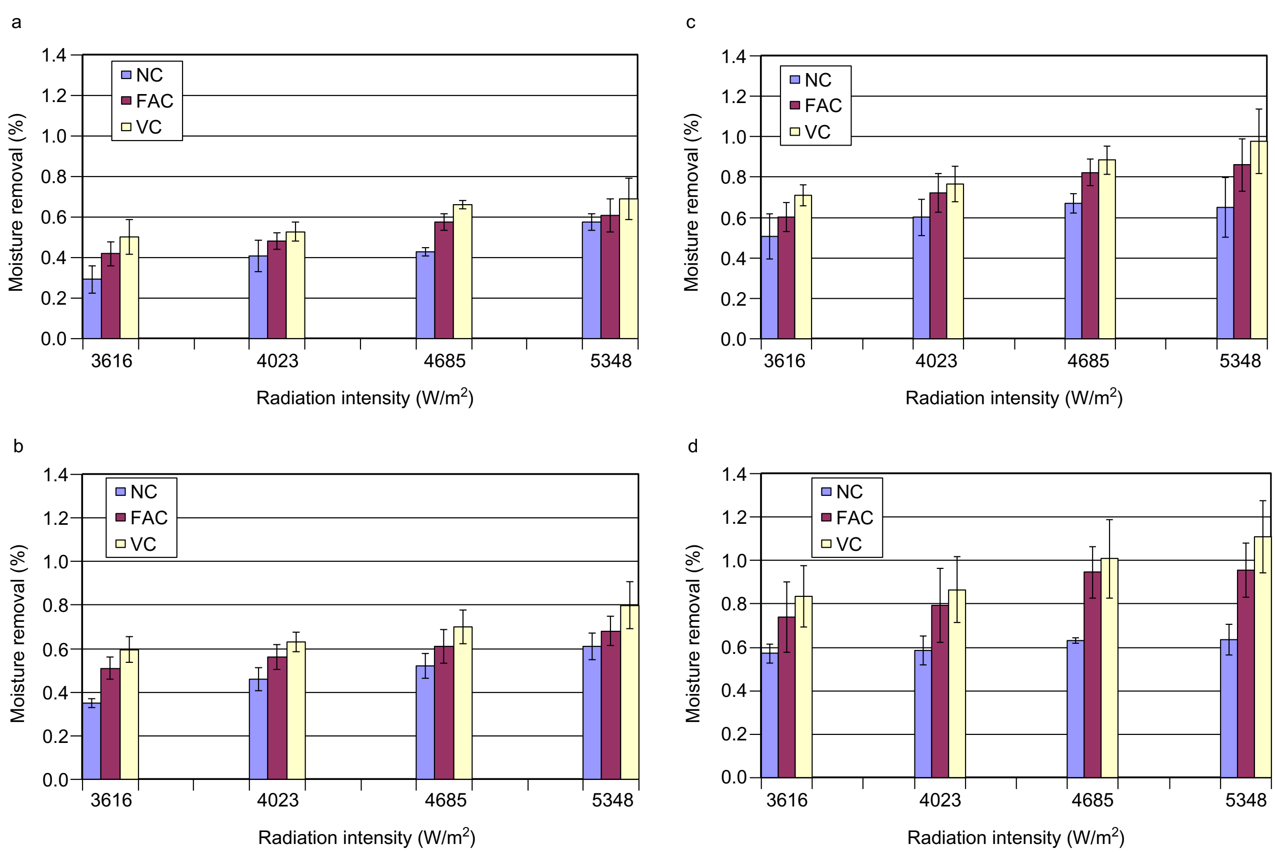

FIG. 7. MOISTURE REMOVAL UNDER DIFFERENT RADIATION INTENSITIES AND COOLING METHODS OF RICE WITH INITIAL MCs (A) 16.7, (B) 20.5, (C) 23.6 AND(D) 25.7%

TABLE 3. TOTAL MOISTURE REMOVAL DURING INFRARED HEATING FOLLOWED BY DIFFERENT COOLING METHODS OF RICE WITH DIFFERENT INITIAL MCs

		Initial moisture content, (%)											
		16.7			20.5			23.6			25.7		
Radiation intensity (W/m^2)	Heating time (s)	IR + NC	IR + FAC	IR + VC	IR + NC	IR + FAC	IR + VC	IR + NC	IR + FAC	IR + VC	IR + NC	IR + FAC	IR + VC
3,616	30	0.4	0.5	0.6	0.6	0.7	0.8	0.8	1.0	1.1	1.1	1.2	1.3
	60	0.7	0.8	0.9	0.9	1.0	1.1	1.2	1.3	1.4	1.4	1.5	1.6
	90	1.0	1.1	1.2	1.2	1.3	1.4	1.5	1.6	1.7	1.7	1.9	2.0
	120	1.2	1.4	1.5	1.4	1.6	1.7	1.9	2.0	2.1	2.0	2.3	2.4
4,023	30	0.6	0.7	0.8	0.8	0.9	1.0	1.1	1.2	1.3	1.2	1.3	1.4
	60	0.9	1.0	1.0	1.1	1.2	1.3	1.5	1.6	1.6	1.5	1.7	1.8
	90	1.2	1.2	1.3	1.3	1.4	1.5	1.7	1.8	1.9	1.8	2.1	2.2
	120	1.5	1.5	1.6	1.7	1.8	1.9	2.1	2.2	2.3	2.2	2.4	2.5
4,685	30	0.9	1.0	1.1	1.0	1.1	1.2	1.3	1.4	1.5	1.4	1.6	1.6
	60	1.1	1.2	1.3	1.2	1.3	1.4	1.7	1.8	1.9	1.7	2.0	2.1
	90	1.3	1.4	1.6	1.6	1.7	1.8	2.1	2.2	2.3	2.2	2.6	2.7
	120	1.7	1.9	2.0	2.2	2.3	2.4	2.6	2.7	2.9	2.8	3.3	3.4
5,348	30	0.9	1.0	1.1	1.2	1.2	1.3	1.4	1.6	1.7	1.6	1.9	2.0
	60	1.4	1.5	1.6	1.6	1.7	1.8	1.8	2.0	2.1	2.1	2.4	2.6
	90	1.7	1.8	1.9	2.1	2.2	2.3	2.3	2.5	2.6	2.7	3.1	3.2
	120	2.1	2.2	2.3	2.8	2.9	3.0	3.1	3.3	3.5	3.2	3.5	3.8

IR, infrared heating; NC, natural cooling; FAC, forced air cooling; VC, vacuum cooling.

total MC removals of rice were 2.1, 2.2 and 2.3, and 3.2, 3.5 and 3.8 percentage points for low (16.7%) and high (25.7%) MC rice, respectively. Similarly, the lowest total MC removals were 0.4, 0.5 and 0.6 and 1.1, 1.2 and 1.3 percentage points for low (16.7%) and high (25.7%) MC rice, respectively, which were achieved at the radiation intensity of 3,616 W/m^2 and heating time of 30 s followed by natural, forced air and vacuum cooling.

The results indicate that up to 3.5 or 3.8 percentage point moisture was removed with the 2 min heating followed by forced air cooling for 5 min or vacuum cooling for 10 min. These rates were much higher than under current commercial practice. Also, Khir *et al.* (2011) found that the moisture diffusivity coefficients during heating and cooling of IR dried rice with tempering were much higher than those of convective drying, which reflected the high drying rate of the IR drying method.

The moisture reductions during cooling were very significant portions of the total removals. For example, 32 and 35% of total moisture removals occurred during cooling when the low initial MC rice was heated for 120 s (about 68C) followed by forced air and vacuum cooling. Similarly, for the high initial MC rice (25.7%), 29 and 34% of total moisture removals occurred during the cooling processes with forced air and vacuum cooling, respectively. This means that IR can be used to heat rough rice with thin layer to a relatively high temperature; it is possible to use the sensible heat from the heated rice to remove more moisture during cooling, which could make the overall IR rough rice drying process more energy efficient. In addition, the tempering process after IR heating may improve moisture removal during cooling and thereby further reduce energy consumption. The effects of tempering after IR heating on moisture removal, rice milling quality and energy savings need to be determined by future research.

CONCLUSION

The results showed that rice can be rapidly dried by using a catalytic IR emitter, a thin layer of rough rice and a relatively short heating period. Rice temperature and moisture removal during IR heating increased with the increase of radiation intensity and heating time. The rice temperature slightly decreased, but the moisture removal increased with initial MC. Natural, forced air and vacuum cooling after IR heating were effective in increasing the total moisture removal. Vacuum and forced air cooling reduced MC more than did natural cooling. Total moisture removal averaged 3.2, 3.5 and 3.8 percentage points for heating at an IR intensity of 5,348 W/m^2 for 120 s followed by natural cooling for 40 min, forced air cooling for 5 min and vacuum cooling for 10 min, respectively. Thin layer drying of rough rice using IR heating followed by cooling could be an effective approach for IR rice dryer design aimed at improving rice drying characteristics and efficiency.

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