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Drying Rates of Thin Layer Rough Rice Drying Using Infrared Radiation

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Abstract. *Rice drying with infrared radiation has been investigated during recent years and showed promising potential with improved quality and energy efficiency. However, due to limited penetration capability of infrared radiation, thin layer drying may be used in infrared dryer design. The objective of this study was to study the moisture removal characteristics of thin layer rough rice heated by infrared radiation and cooled with various methods, including natural cooling, forced air cooling and vacuum cooling. The rewetted rough rice samples with four different moisture contents, 16.7, 20.5, 23.6 and 25.7 % (wb), were dried with four different radiation intensities, 3616, 4023, 4685, and 5348 W/m^2, for four exposure times, 30, 60, 90, and120 s. The achieved grain temperatures ranged from 35.1ºC to 68.4ºC under the tested heating conditions. The vacuum and forced air cooling methods had more moisture removal than the natural cooling. The total moisture removal reached to 3.2, 3.5, and 3.8 percentage points for the rice heated to the temperature of 63.5 ºC achieved with the infrared intensity of 5348 W/m^2 and heating time of 120 s and followed by the natural cooling for 40 min, forced air cooling for 5 min and vacuum cooling for 10 min, respectively. It was concluded that infrared radiation thin layer drying of rough rice followed by cooling could be an effective approach to design infrared rice dryer for improving the drying rates and reducing energy consumption*.

Keywords. Infrared radiation, drying, rice, quality, cooling

Introduction

Moisture content 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 the moisture content much higher than the required moisture for safety storage. In order to obtain the safe storage moisture, rough rice is normally dried with heated air after harvest. However, the heated air drying is a slow process and energy intensive, which negatively impacted on the economics of rice production.

Only relatively low temperature of heated air is used in rice drying process to avoid the damage in 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 into the drying air. As the moisture is removed from the outer layers of the grain, moisture and temperature gradients are established within the kernel. These gradients cause stresses in the grain, resulting in the rice kernel to break during milling (Ban, 1971; Kunze and Choudhury, 1972; Kunze, 1979).Therefore, to minimize the moisture gradient generated during conventional rice drying the typical drying process uses the low heated air temperature up to 54ºC and multiple drying passes by removing relatively small amount of moisture (2%-3%) in each pass (Kunze and Calderwood, 1985). In addition, the prolonged drying process due to the low drying temperature has low energy efficiency and may still cause certain loss in rice quality. It is important to develop a drying method that can be shorten the drying time with reduced energy consumption and maintained rice milling quality.

Infrared (IR) radiation has received considerable attention lately because of its advantages in shortening drying time, high energy transfer rate, energy savings, and superior product quality compared to conventional heated air drying (Afzal et al., 1999; Tan et al., 2001). It could be used as an energy saving drying method with improved drying efficiency, space saving and clean working environment (Ratti and Mujumdar, 1995).

The combination of convection and infrared radiation has appeared as one of the potential additions to the traditional drying methods for improving the drying efficiency. Afzal et al. (1999) found that within temperature ranges of 40ºC to 70 ºC, a combined hot air-FIR drying process in comparison with convection drying reduced total energy required by about 156% ,238 % and 245% when compared with convection drying alone at 40ºC, 55ºC and 70ºC ,respectively. It has been suggested using the combination of far infrared (FIR) and convection for drying cereals and vegetables (Sandu, 1986; Afzal and Abe, 1997). The recent advances in rough rice processing have emphasized the need for the improvement in the drying techniques to achieve high drying rates. The direct application of infrared radiation energy for preheating the rice in conjunction with heated air drying has shown considerable prospect for increasing the drying rate. The temperature increase of rice kernel caused by the IR heating results in the increased the vapor pressure in the grain, which promote the migration of moisture to the surface of the grain. Then the moisture can be removed by the ventilating air during the drying process. Consequently, preheating the rice prior to exposure to drying air should increase the drying rate during heated air drying. Satish et al. (1970) summarized some advantages of using IR for preheating grains in drying process, which include (a) high rate of heat transfer, (b) efficient transmission through the air or evacuated space, (c) cleanliness, (d) compactness of equipment, and (e) ease of automation.

In addition to the synergistic effect on the improvement in drying efficiency due to the combination of infrared with heated air. IR impinges on the material surface and penetrates it when a material is exposed to IR radiation. The increased molecular vibration due to absorption of radiation generates heat in the material both at surface and inner layers simultaneously, which increase the heating rate. The rapid heating of the material increases the rate of moisture movement towards the surface and results in increased mass transfer (Sakai and Hanzawa, 1994 and Hebber, et al., 2004).

Vacuum cooling is a relatively rapid cooling method for porous and moist foods and agricultural products. The heat of food body is released by evaporating the water within the foods under vacuum pressure directly. Weight loss inherently occurs during vacuum cooling since the cooling effect comes from water evaporation (Wang and Sun, 2001). The advantages of vacuum cooling include shortened time, extended product shelf life and improved product quality and safety, which has been demonstrated by the food processing industry. Vacuum cooled products are also found to have a much more uniform internal temperature distribution as compared to products cooled using conventional cooling methods (Zheng and Sun, 2004).

Combining IR radiation heating and vacuum to perform a drying operation is based three considerations. IR radiation heating speeds up the drying because of their ability to heat up the product in an instantaneous and homogeneous way for products with small dimensions. Vacuum enhances the mass transfer because of an increased pressure gradient between the inside and the outside of the product. The pressure in the vacuum chamber is reduced by a vacuum pump, and as the pressure decreases, the boiling point temperature of water is lowered. When the boiling point of the water reaches the initial product temperature, the water from the product begins to evaporate. The evaporating water requires energy, which comes from the sensible heat of the product (Rennie et al., 2001). The IR radiation heating coupled with vacuum could speed up the drying process, improve energy efficiency and improve the product quality (Mongpraneet et al., 2002).

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. When IR was used to preheat rough rice to 60ºC followed by 49 ºC heated air drying for 2-3 min, approximately 2% MC was removed by each pass (Schroeder and Rosberg, 1960; Schroeder, 1960 and 1961; hall, 1962). It also reported that it took only 7 minutes to reduce the moisture content from 20% to 14.8% (db) using near infrared heating compared to 30 minutes used for hot air drying (Rao, 1983). In addition, Bekki (1991) found that the maximum absorption of infrared radiation by medium grain rough rice occurred at wavelength of 2.9µm. The maximum depth of penetration into agricultural produce has been found to be 18 mm (Sandu, 1986). Thus, the application of IR heating for achieving high drying rate should be focused on thin layer drying.

Since IR can be used to heat rough rice with thin layer quickly to a relatively high temperature, it is possible to use the sensible heat from the heated rice to remove more moisture during cooling. The IR heating process by cooling treatment could improve rice drying rate and total moisture removal in each drying pass and make the overall IR rough rice drying more energy efficient. However, no reports are available on such aspect.

The objectives of this research were to (1) study the effects of operating parameters of the infrared dryer, including radiation intensity, exposure time and initial moisture content, on the grain temperatures and the moisture removal of thin layer rough rice, (2) investigate the effectiveness of various cooling methods, including natural cooling, forced air cooling and vacuum cooling, for removing additional moisture after the IR heating, and (3) develop regression models for predicting the rice temperatures and moisture removals based on the operation parameters.

Material and Methods

Infrared drying device

A laboratory scale infrared dryer was developed in the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis. The infrared dryer comprised of two components, infrared emitter and drying bed. The catalytic emitter provided by Catalytic Industrial Group (Independence, Kansas) was used as infrared radiation source. The emitter generated IR 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 30x60 cm with surface temperature at about 730 ºC with corresponding peak wavelength 3.6µm assuming the emitter as a blackbody. The heater surface temperature was measured by type-T thermocouples embedded at eight different locations on the heater surface. An aluminum box with dimension of 65cm (length) x 37cm (width) x 45cm (height) was installed around the emitter as wave guide to achieve the uniform intensity at the rice bed surface. The dimension of the drying bed was 90 cm (length) x 35 cm (width) x 7 cm (depth) made from an aluminum sheet of 3 mm thickness to minimize energy loss. Two type-T thermocouples were embedded on the bed surface to measure the bed temperature.

The rice bed was set at 5, 10, 15 and 20 cm below the bottom edge of the wave guide with corresponding average IR intensities of 3616, 4023, 4685, and 5348 W/m^2 at the rice bed surface. The radiation intensity was measured by using Ophir FL205A Thermal Excimer Absorber Head (Ophir,Washington, MA).

Rewetting procedures

Rough rice, medium grain rice M202, with moisture content of 12.2 ± 0.3% (db) obtained from Pacific International Rice Mills, Inc (Woodland, California) was used for this study. The rice samples with high initial moisture contents were obtained by rewetting the rough rice for 48 h then aerated for 1h 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 moisture content to reach the targeted moisture contents. The rewetted rough samples were placed in Zip lock bags and stored for one week at 4 ºC. After one week storage the samples were allowed sufficient time (about three hours) to become equilibrium at the room temperature before the drying test. Before the drying test the moisture content of the samples were determined by the air oven method (130 ºC for 24h) (ASAE, 1995) and all reported moisture contents are on wet basis. The initial moisture contents of the samples were 16.7 ± 0.2 %, 20.5 ± 0.3%, 23.6 ± 0.3%, and 25.7±0.25 %.

Drying procedures

The numbers of total drying tests were 128 with four initial moisture contents (16.7, 20.5, 23.6, and 25.7 %), four IR radiation intensities (3616, 4023, 4685, and 5348 W/m^2) and four heating time durations (30, 60, 90, and 120 s). All tests were replicated at each condition. For the drying test, a 600 g rice sample was placed on the drying bed as a thin layer of 10 ± 4 mm with loading rate of 5.3 kg /m^2. The initial drying bed temperature was 35 ºC.

To determine the drying characteristics under different heating conditions, the rice temperature and moisture loss were measured at the end of each heating period. The rice temperature was measured by thermometers (Solomat MPM 500, UK) and (Visor Handspring Inc., U.S.A.). The rice sample weight was measured using a balance with two-decimal accuracy before and after heating. The weight loss during infrared heating and the original moisture content were used to calculate the moisture removal (difference between the original and final moisture contents) expressed as percentage points.

Cooling procedures

In order to study the effects of cooling methods on the additional moisture removal after the IR heating, three cooling methods, including natural cooling, forced air cooling and vacuum cooling, were tested. Each sample after the IR heating was divided into three samples to conduct the cooling processes by placing the sample on the cooling bed as a thin layer of 10 ± 4 mm. The weight and temperature of the sample were measured at the beginning and end of the cooling process. The cooling times were 20-40, 5 and 10 min for natural cooling, forced air cooling and vacuum cooling. At the end of cooling, the sample temperature was close to the room temperature. The natural and forced air cooling treatments were achieved by using ambient air; the air velocity of forced air cooling was 0.1m/s which is similar to commercial drying practice. The vacuum cooling was conducted by placing the samples in a vacuum oven (THELCO. Chicago-IL.60647 U.S.A) set at room temperature and pressure of 98.2 kPa. The weight loss during cooling processes and the moisture content after infrared heating were used to calculate the moisture removal during the cooling processes.

Results and Discussions

Rice temperatures

In general, the temperatures of heated rice samples ranged from 35.1 to 68.4 ºC under the tested conditions. The rice temperature increased with the increase of heating duration and the radiation intensity for the rice samples with the same initial moisture content and decreased slightly with the increase of initial moisture content. Fore example, The temperatures of heated rice samples increased from 36.5, 36.3, 36 and 35.1ºC to 68.4, 66.5,64.7 and 63.5 ºC by increasing heating time from 30 s to 120 s and radiation intensity from 3616 W/m^2 to 5348 W/m^2 for rice samples with initial moisture contents 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. The rice sample temperatures with different heating durations at different initial moisture contents and radiation intensities are presented in table1. The average differences were 1.7±0.5, 3.2±0.6, 1.6 ± 0.6, 2.6 ±0.6 and 1±0.2ºC between the samples with moisture contents 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 level (5348 W/m^2) was 4.3±0.7ºC between the low MC rice (16.7%) and high MC rice (25.7 %). The results indicated that the effect of initial moisture content on rice temperature was relatively small compared to IR intensity and heating time. A high correlation between the average rice temperature and heating time were obtained as the linear model which can be used to predict the temperature change with known heating time and radiation intensity under the tested initial moisture range and drying bed temperature (fig. 1).

Table 1.Rice temperatures during infrared heating under different radiation intensities, heating times and initial moisture contents

Radiation intensity (W/m^2)	Heating time (s)	Rice grain temperatures (ºC) MC 16.7 %	MC 20.5%	MC 23.6%	MC 25.7%
	30	36.5	36.3	36.0	35.1
	60	40.8	40.0	39.2	38.7
3616	90	46.0	45.6	44.5	44.0
	120	50.5	49.2	48.7	48.3
	30	41.0	39.0	38.2	38.0
4023	60	43.7	43.0	42.0	41.3
	90	49.7	48.8	47.5	46.7
	120	52.2	52.0	51.0	49.6
	30	43.8	42.8	41.0	40.0
	60	48.7	47.3	46.7	46.0
4685	90	55.0	53.2	52.8	51.7
	120	58.7	56.5	55.4	54.3
	30	49.2	47.0	46.2	45.1
	60	55.0	54.0	52.5	51.7
5348	90	62.0	60.5	58.3	57.3
	120	68.4	66.5	64.7	63.5

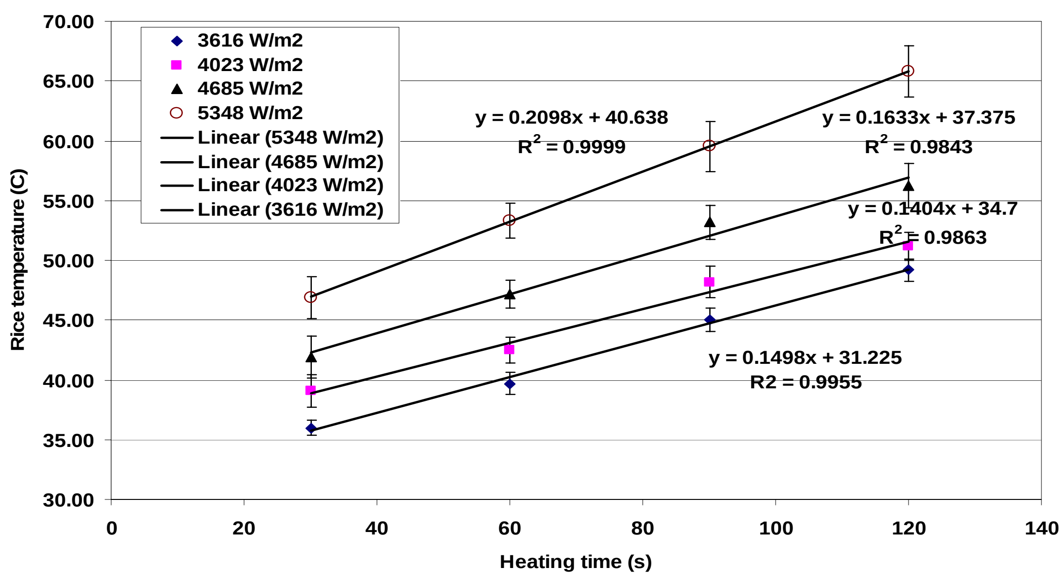

Figure1. Relationship between average rice temperature and heating time under different radiation intensities.

In order to accurately predicting the rice temperatures under various operating conditions, which is important in the design of drying systems a multiple linear regression model was obtained using the Sigma Stat software (Version 2.0, Jandel corporation, San Rafael ,CA).

Rice temperature (ºC) = 8.424 + 0.166 * Ht + (0.00792 * RI -0.344 * IMC

In the model, the operation parameters, heating time Ht (s), radiation intensity RI (W/m^2) and initial moisture content IMC (% wb) are independent variables. The model has r^2 value of 0.975, which indicate that the model can be used for predicting the rice temperature under the IR heating.

Moisture removals during infrared heating

The results of moisture removals for rice samples with different initial moisture contents, heating times and radiation intensities are shown in figs. 2 to 5.

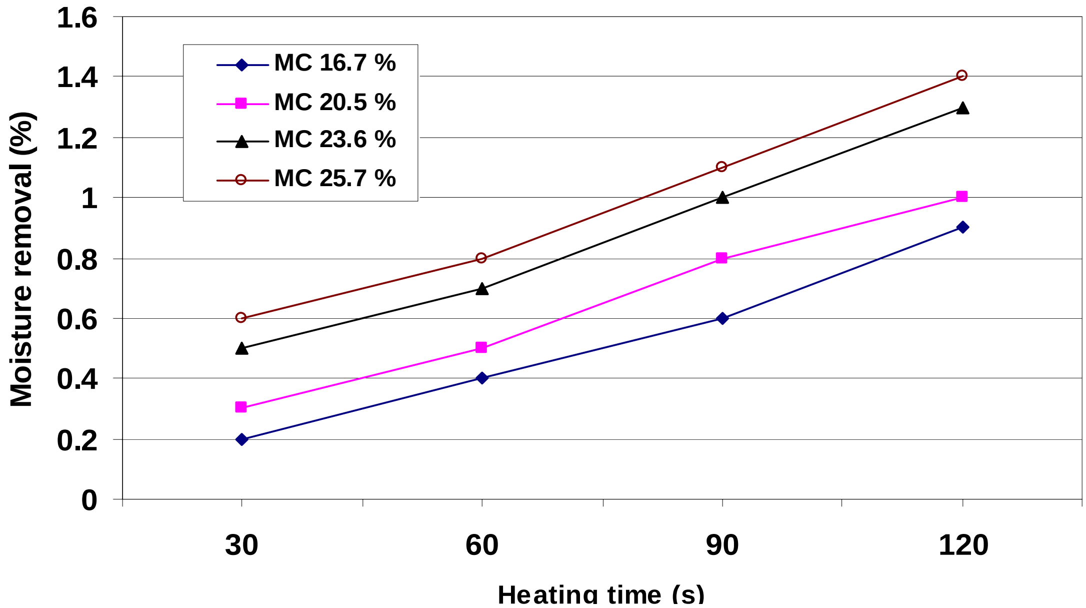

Figure 2. Effect of heating time on moisture removal of rice with different initial moisture contents at radiation intensity of 3616 W /m^2.

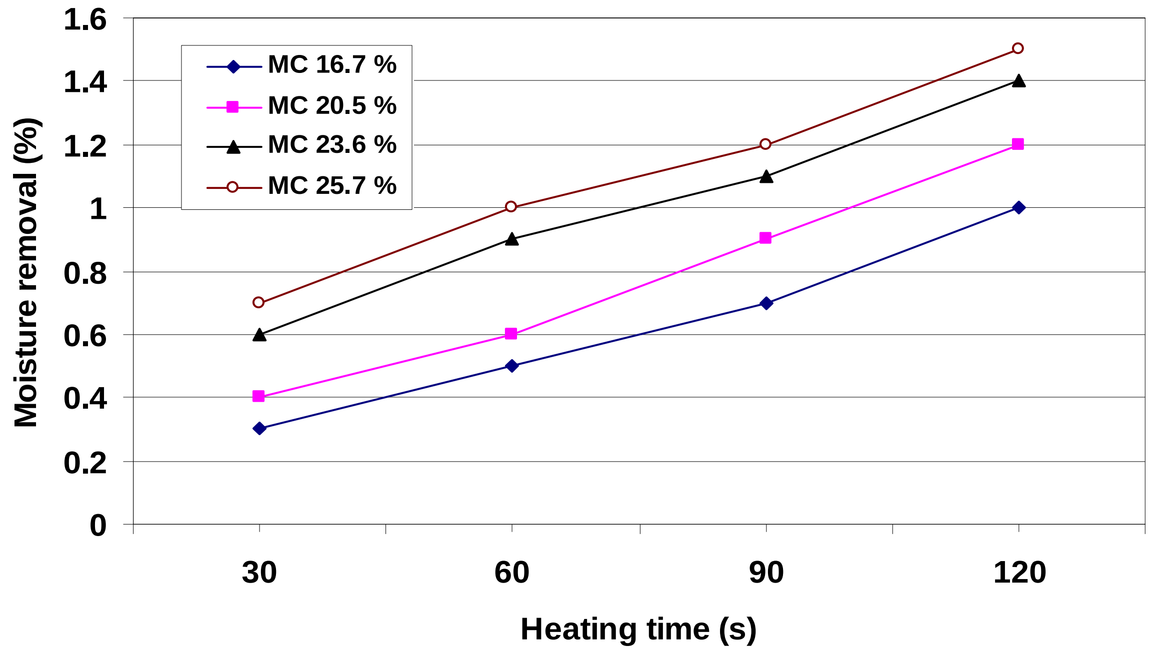

Figure 3. Effect of heating time on moisture removal of rice with different initial moisture contents at radiation intensity of 4023 W /m^2.

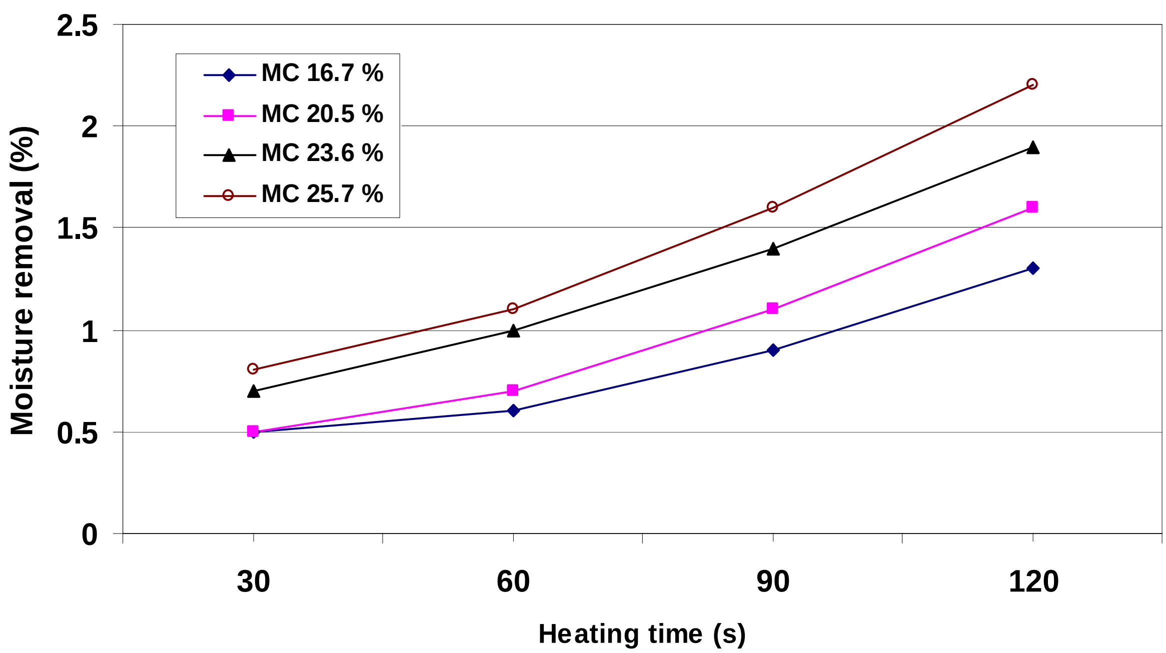

Figure 4. Effect of heating time on moisture removal of rice with different initial moisture contents at radiation intensity of 4658 W /m^2.

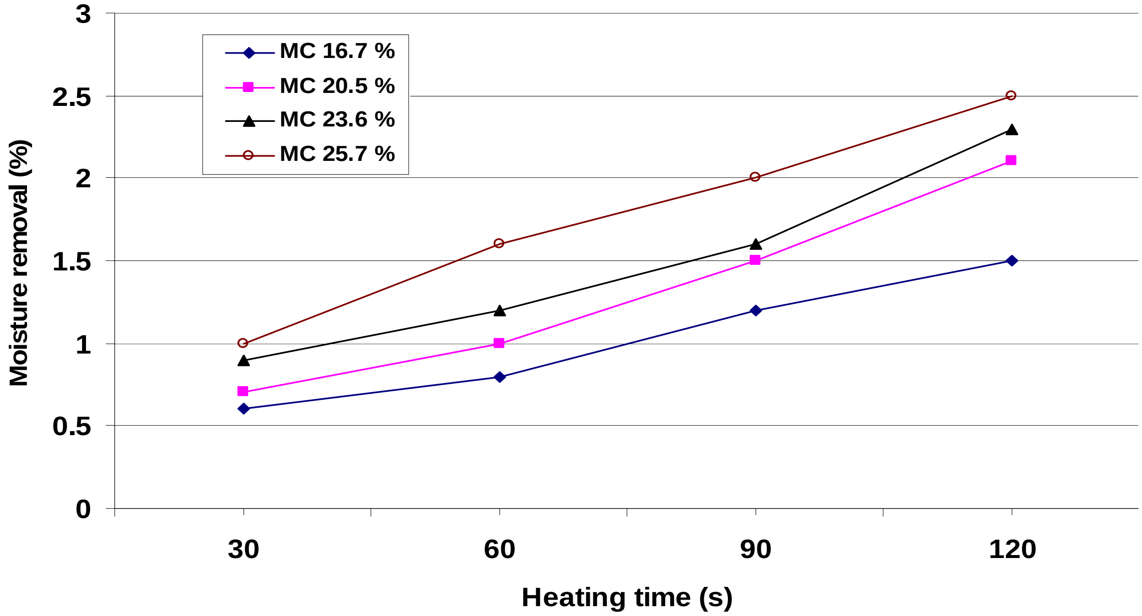

Figure 5. Effect of heating time on moisture removal of rice with different initial moisture contents at radiation intensity of 5348 W /m^2.

It is apparent that the rice moisture removal increased with the increased heating time under specific radiation intensity and an initial moisture content which was due to more energy absorbed by the rice kernels with longer heating time and caused more water evaporated compared to shorter heating time.

The moisture removal results also clearly showed that more moisture was removed from the rice with high initial moisture content. For example, the moisture removals increased from 0.2 percentage points to 0.6 percentage points by increasing the initial moisture content of from16.7 to 25.7 % for the rice samples heated for 30 s under radiation intensity of 3616 W/m^2. Also, the moisture removals increased from 1.5 percentage points to 2.5 percentage points by increasing the initial moisture content from16.7 to 25.7 % for the rice samples heated for 120 s under radiation intensity of 5348 W/m^2. Linear models with a high correlation between the rice temperature and the moisture removal were obtained. The predicted and experimental results are shown in fig. 6.

A multiple linear regression model was also obtained using Sigma Stat software (Version 2.0, Jandel corporation, San Rafael ,CA) with independent variables of heating time Ht (s), radiation intensity RI (W/m^2) and initial moisture content IMC (% wb).

$$\text{Moisture removal (\%)} = -2.814 + 0.0109 * Ht + 0.000377 * RI + 0.0634 * IMC$$

The model has the r^2 value of 0.93 which could be used for predicting the rice moisture removal with the known drying conditions.

It is important to notice that the drying rate decreased as the initial moisture content of the rice decreased, but it increased with the increase of radiation intensity. For example, the average drying rates for the rice samples with the low (16.7 %) and high moisture content (25.7 %) were 0.43, 0.53, 0.71, and 0.88 percentage points per minute and 0.83, 0.97, 1.18, and 1.46 percentage points per minute at radiation intensities of 3616, 4023, 4685, and 5348 W/m^2 .

The linear models with the high correlation between the radiation intensity and average drying rate were obtained, which can be used to predict the drying rate with under the tested moisture range and bed drying temperature (fig.7).

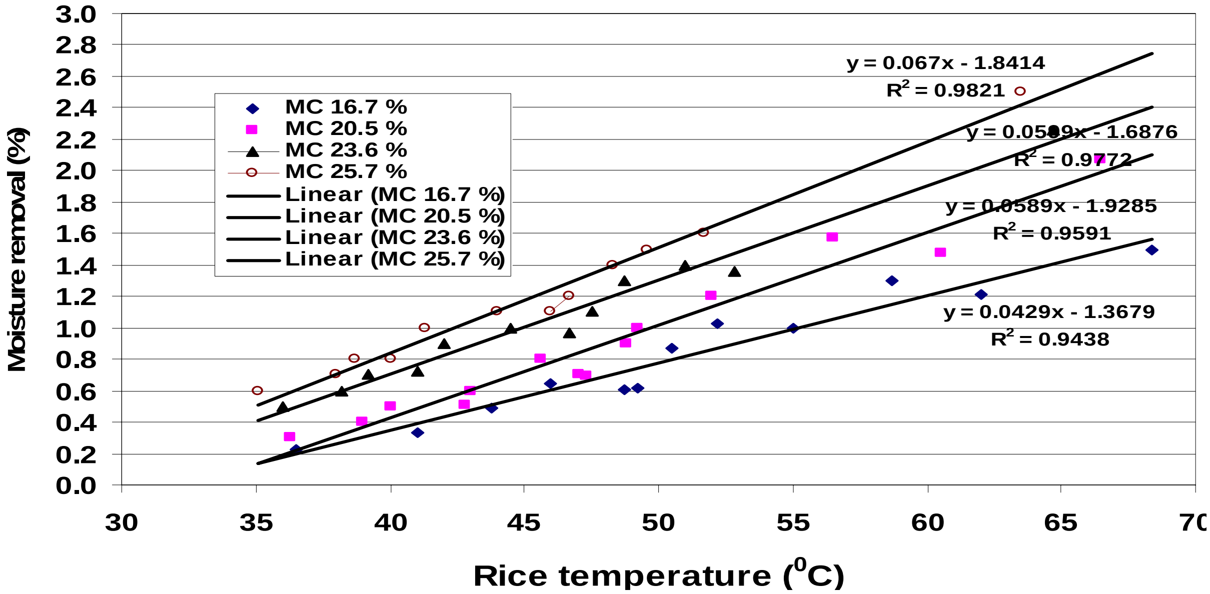

Figure 6. Relationship between rice temperature and moisture removals with different initial moisture contents.

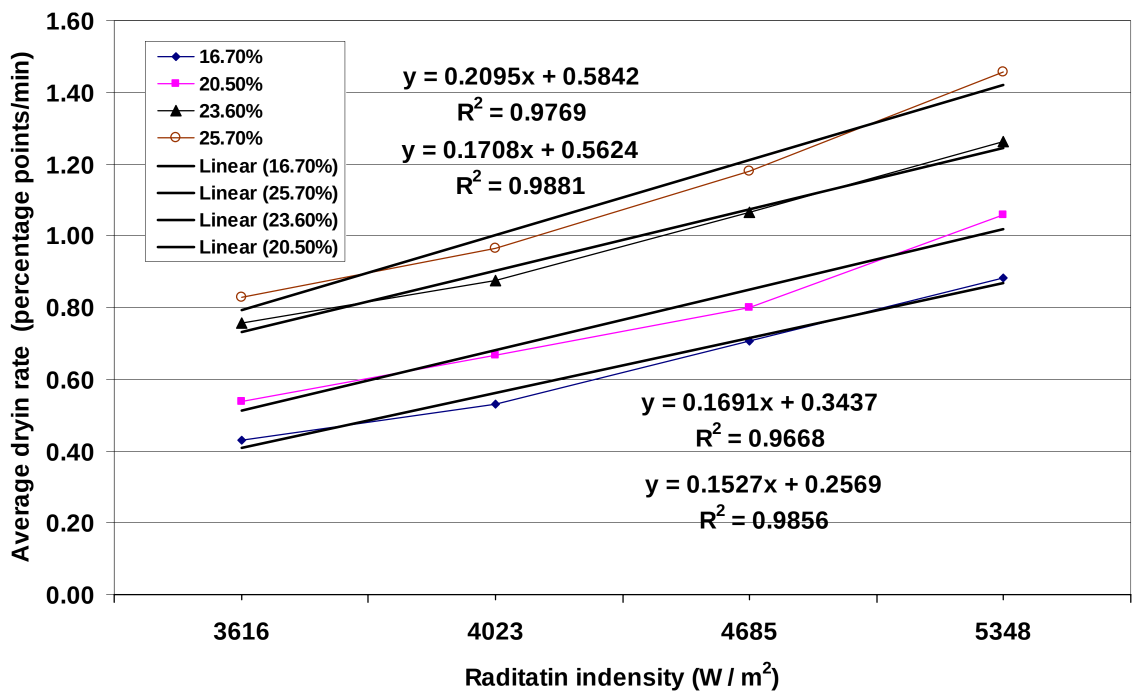

Figure 7. Relationship between radiation intensity and drying rate average with different initial moisture contents.

Moisture removals with different cooling methods

The moisture removal results of rice samples with different initial moisture contents and cooling methods are shown in figs 8 to 11. In general, the vacuum showed the largest amount of moisture removal, followed by forced air cooling and natural cooling when the other conditions were the same. The average moisture removals by vacuum cooling, forced air cooling and natural cooling were 0.3, 0.4, and 0.5 percentage points at radiation intensity 3616 w/m^2 and 0.57, 0.6 and 0.7 percentage points at radiation intensity 5348 w/m2 for the low moisture rice (16.7%), which compared to 0.6, 0.7, and 0.8 percentage points at radiation of 3616 w/m^2 and 0.64, 1.0, and 1.1 percentage points at the IR intensity of 5348 w/m^2 for the high moisture rice (25.7%), correspondingly. The vacuum cooling had more 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 moisture content and processed with the highest radiation intensity.

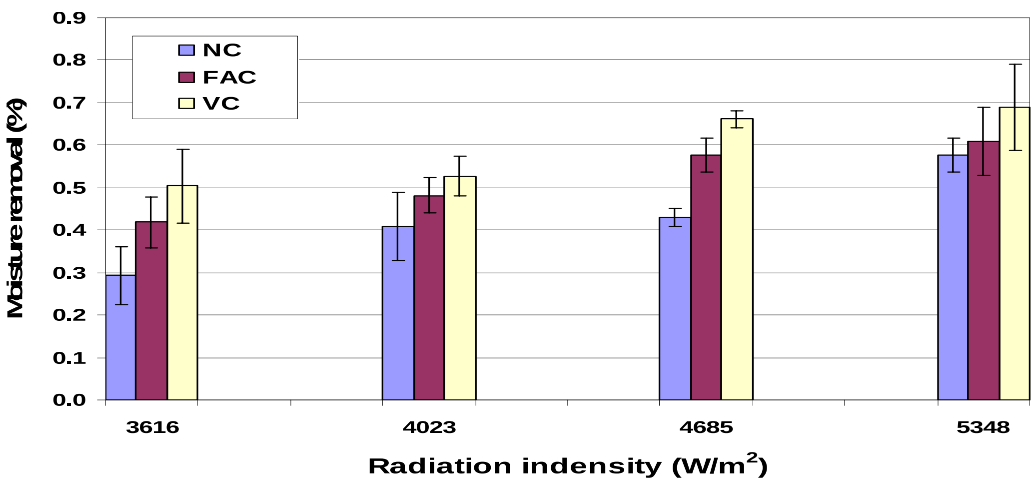

Figure 8. Moisture removal with different radiation intensities and cooling methods of rice with initial MC of 16.7 %

(NC-natural cooling, FAC-forced air cooling, VC- vacuum cooling)

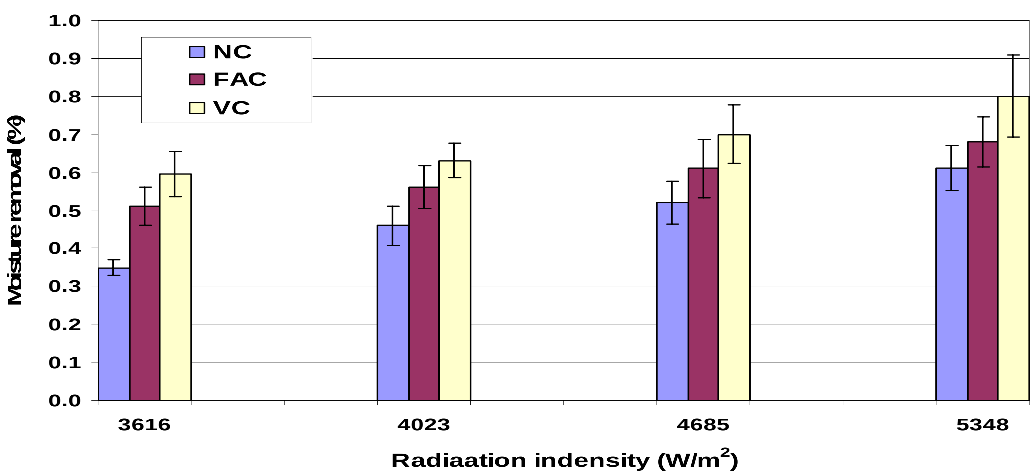

Figure 9. Moisture removal with different radiation intensities and cooling methods of rice with initial MC of 20.5 %

(NC-natural cooling, FAC-forced air cooling, VC- vacuum cooling)

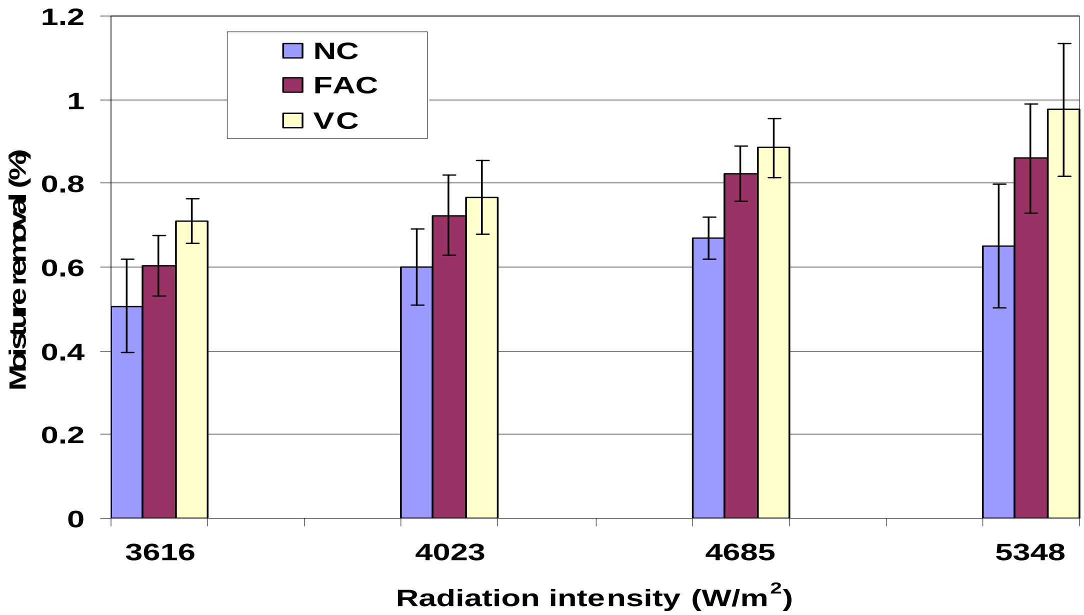

Figure10. Moisture removal with different radiation intensities and cooling methods of rice with initial MC of 23.6 %

(NC-natural cooling, FAC-forced air cooling, VC- vacuum cooling)

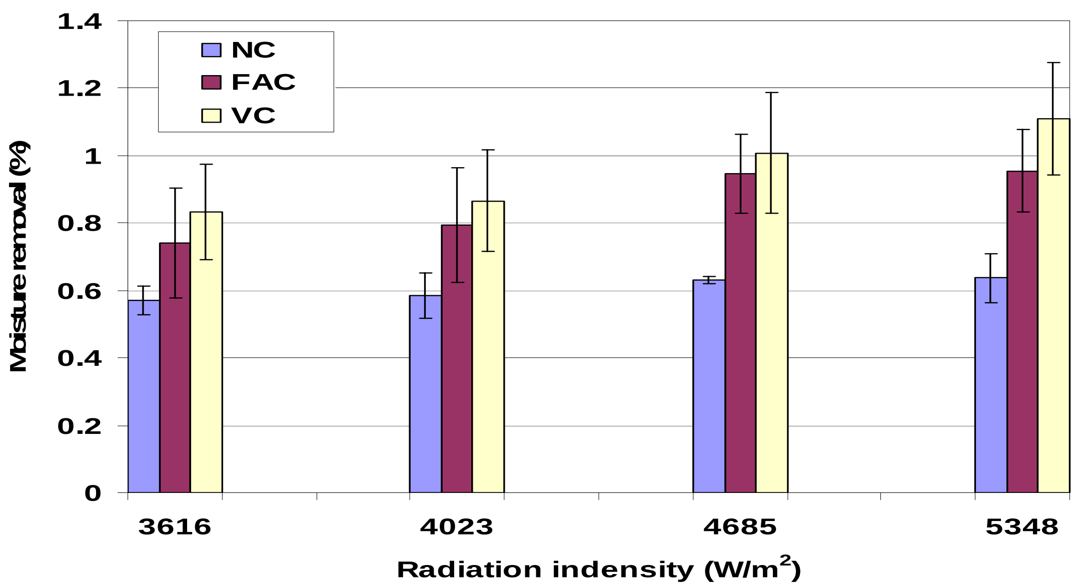

Figure11. Moisture removal with different radiation intensities and cooling methods of rice with initial MC of 25.7 %.

(NC-natural cooling, FAC-forced air cooling, VC- vacuum cooling)

Total moisture removals

The total moisture removal results from infrared heating and cooling had a parallel trend between the moisture removal and heating time for the different cooling methods (fig. 12 and13). For the three cooling methods, the highest 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) IMC rice, respectively, which were achieved at the radiation intensity of 5348 w/m^2 and heating time of 120 s followed by natural cooling, forced air cooling, and vacuum cooling (figs 12d and 13d). 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%) IMC rice, respectively, which were achieved at the radiation intensity of 3616 W/m^2 and heating time of 30 s followed by natural, forced air and vacuum cooling (figs 12a and 13a).

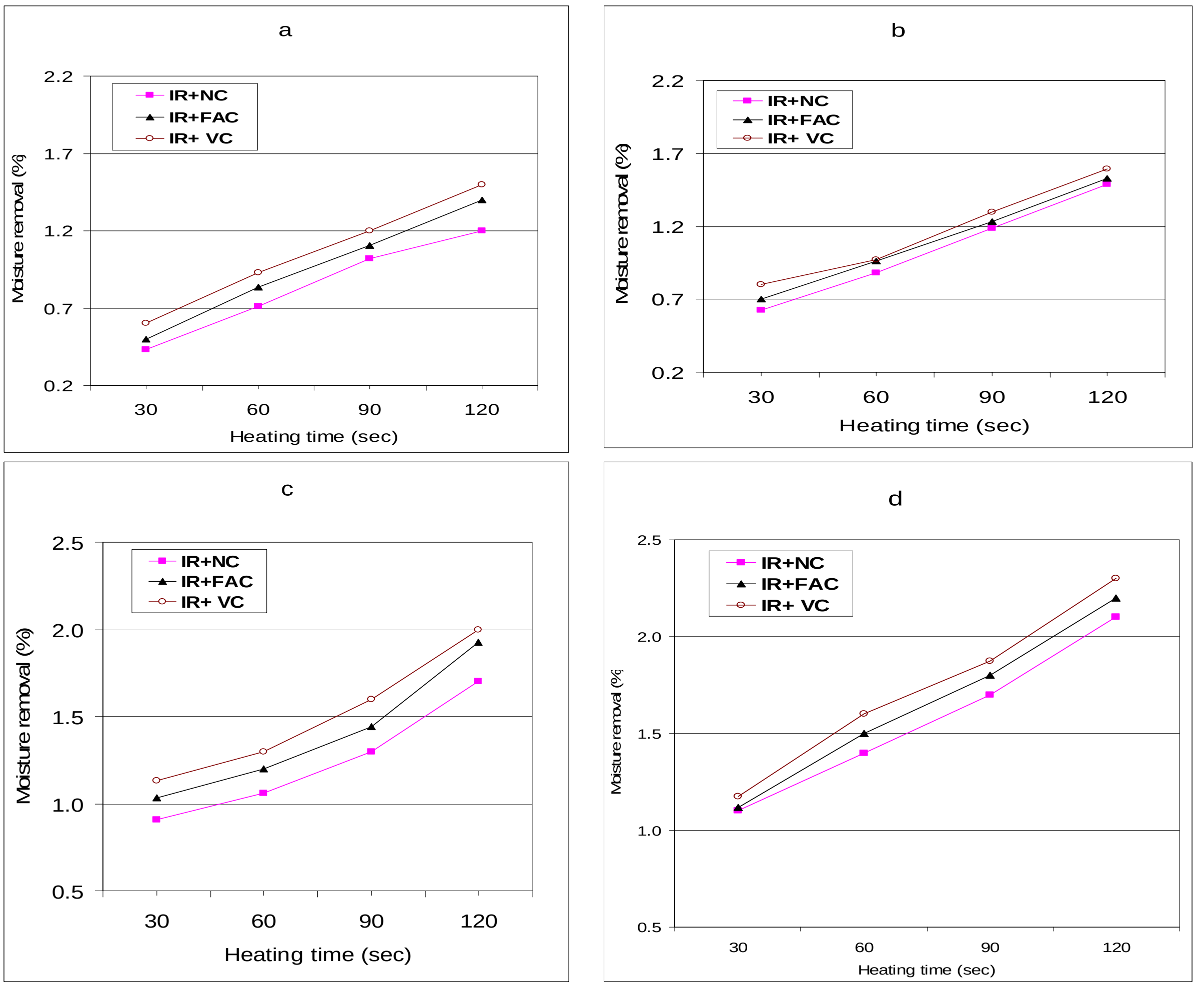

Figure 12.Total moisture removal of rice with initial MC of 16.7 % during infrared heating

(a - 3613 W/m2, b - 4023 W/m2, c - 4658 W/m2, d - 5348 W/m2) followed by different cooling methods.

(IR- infrared heating, NC-natural cooling, FAC-forced air cooling, VC- vacuum cooling)

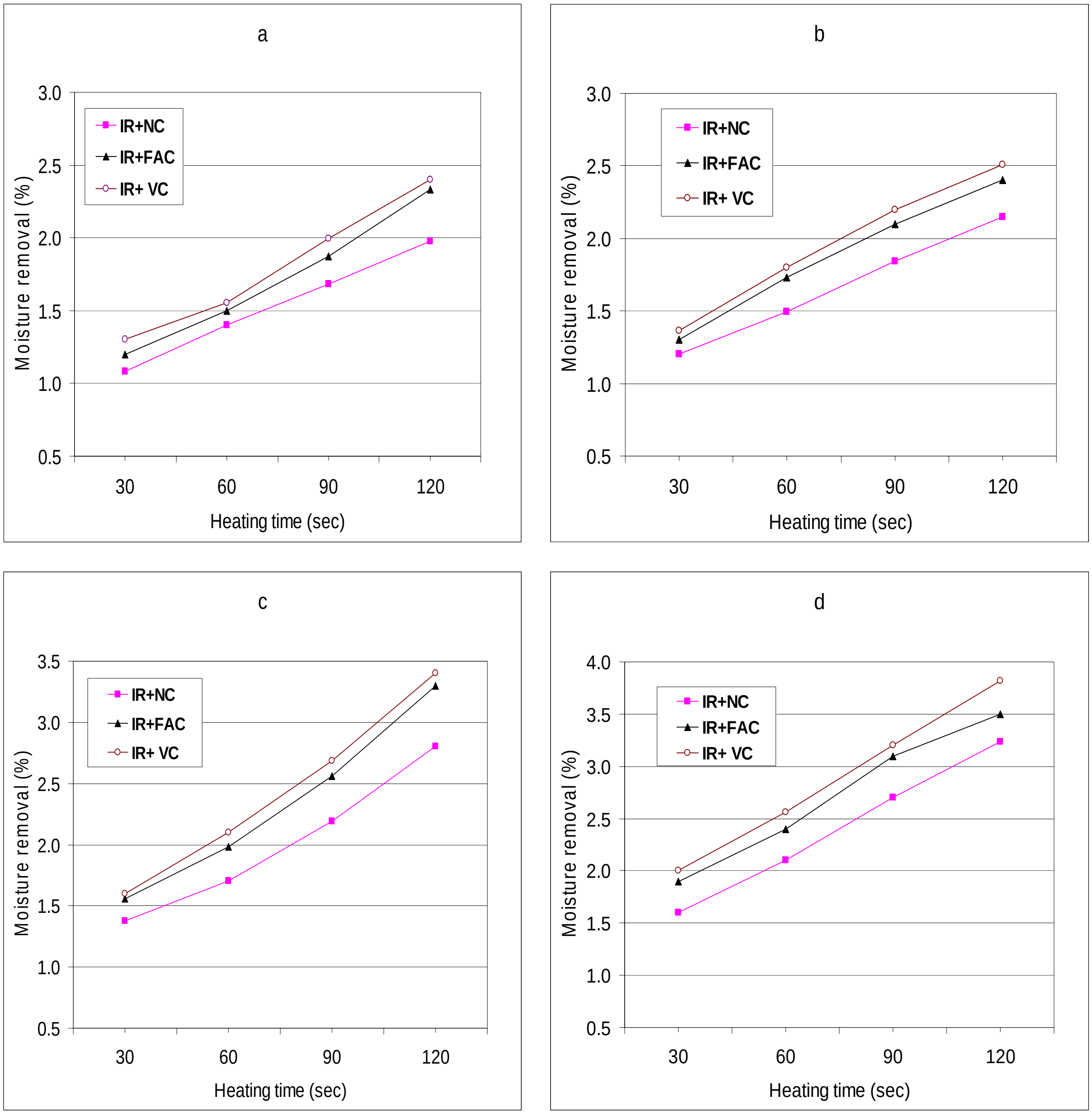

Figure 13.Total moisture removal of rice with initial MC of 25.7 % during infrared heating

(a - 3613 W/m2, b - 4023 W/m2, c - 4658 W/m2, d - 5348 W/m2) followed by different cooling methods.

(IR- infrared heating, NC-natural cooling, FAC-forced air cooling, VC- vacuum cooling

The above 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 five min or vacuum cooling for ten min. 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 heated air drying.

Compared to the total moisture removals, the moistures removed during cooling were very significant portions. For example, 32% and 35% of total moisture removals occurred during cooling when the low IMC rice was heated for 120 s (about 68ºC) followed by forced air and vacuum cooling. Similarly, for the high IMC rice (25.7%), 29% and 34% of total moisture removals occurred during the cooling processes with forced air and vacuum cooling, respectively.

Because the tempering process after infrared heating may improve the moisture removal during cooling period, it may further reduce the energy consumption due to no heating needed during cooling. The amount of energy saving and consumption still need to be determined in the future research.

Conclusion

The research results showed that high rice drying temperature can be achieved at a relatively short heating time by using catalytic IR emitter with thin-layer of rough rice. The 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 the increase of initial moisture content. The natural, forced air and vacuum cooling processes after the IR heating were effective for increasing the total moisture removal with infrared drying. The vacuum and forced air cooling showed more moisture removal than natural cooling. The total moisture removal reached to 3.2, 3.5 and 3.8 percentage points for heating with the IR intensity of 5348 W/m^2 for 120 s and rice temperature of 63.5ºC followed by natural cooling for 40 min, forced air cooling for 5 min and vacuum cooling for 10 min, respectively. It was concluded that thin layer rough rice drying using infrared radiation followed by cooling could be an effective approach for infrared rice dryer design aiming at improving rice drying characteristics and efficiency.

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