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Moisture diffusivity of rough rice under infrared radiation drying

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ABSTRACT

To design efficient infrared (IR) dryers for rough rice, it is important to understand the drying behavior of rough rice under IR heating. The objective of this study was to determine the moisture diffusivity of rough rice under IR heating followed by cooling. The effects of initial moisture content, rice temperature, drying bed thickness, tempering, and cooling methods on moisture diffusivity and moisture diffusivity coefficient were investigated. Samples of freshly harvested medium grain rice (M202 variety) with initial moisture content (MC) of 25.8, 31.2 and 33.8 g moisture/100 g dry solid were used. They were dried with IR radiation intensity of 5348 W/m^2, for six exposure times, 15, 30, 40, 60, 90 and 120 s. The tested drying bed thicknesses were single-layer, 5 mm and 10 mm. The unsteady diffusion equation based on Fick's law and slope methods were used to describe moisture diffusivity. The results indicated that rough rice moisture diffusivities under IR heating and cooling were significantly affected by rice temperature and tempering treatment, respectively. High heating rate and moisture diffusivity were achieved with IR heating. It took only 60, 90 and 120 s to achieve about 60 °C rice temperature with corresponding moisture diffusivities of 4.8×10^{-9}, 3.6×10^{-9} and 3.4×10^{-9} m^2/s during heating for drying bed thicknesses of a single layer, 5 mm and 10 mm, respectively. 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.

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1. Introduction

Infrared (IR) radiation drying has been investigated as a potential method for obtaining high quality dried foodstuffs, including fruits, vegetables, rice and other grains (Abe & Afzal, 1997; Afzal & Abe, 1998, 2000; Hebbar & Rostagi, 2001; Zhu, Zou, Chu, & Li, 2002). IR radiation drying is fundamentally different from convection drying because the material is dried directly by absorption of IR radiation rather than transfer of heat from air (Bal, Wratten, Chesnen, & Faulkner, 1970). IR radiation energy is transferred from the heating element to the product surface without heating the surrounding air. The radiation impinges on the exposed material and penetrates it and then is converted to sensible heat (Ginzburg, 1969, pp. 174–254). This penetration could provide more uniform heating and may reduce the moisture gradient in rice kernels during heating and drying. Also, since IR does not heat up the medium, the temperature of the rice is not limited by the wet bulb temperature of the air, so high rice temperatures could be achieved in a short time for quick moisture removal. In addition, after IR heating, displacement of moisture from the kernel's core towards its surface can be achieved by applying tempering to reduce the moisture gradient. IR heating offers many potential advantages over conventional drying: high drying rate, high energy efficiency, high quality finished products, uniform temperature in the product during drying, and less dust generation because less air flows across the product (Sharma, Verma, & Pathare, 2005).

During a drying process, heat and mass transfer normally occur simultaneously. Suitable knowledge and control of mass transfer are essential to both the quality of the product and the economics of the process. The difficulties of applying moisture diffusivity phenomena theory to food processes arise from the complex physical structure and composition of foods, which may vary even within the same food sample and may change during processing (Rao, Sayed, & Ashim, 2005).

Drying of cereal grains, including rice, mostly occurs in the falling rate period and the moisture transfer during drying is controlled by internal moisture diffusion (Saravacos & Charm, 1962; Wang & Brennan, 1992). Fick's second law of diffusion has been widely used to describe the drying process during the falling rate

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period for most biological materials (Sablani, Rahman, & Al-Habsi, 2000; Saravacos & Charm, 1962; Saravacos & Maroulis, 2001).

Moisture diffusivity is an important physical transport property which is useful in the engineering analysis of basic food processing operations such as drying. Diffusion phenomena are extremely complex, so reliable data are scarce, especially for IR drying. As a consequence, traditional food processing involving diffusion has been mainly based on experimental knowledge. Accurate data on moisture diffusivity of food products are essential for efficient and effective design of food processing operations, including drying (Zhao, 1988).

Limited data on rice moisture diffusivities under IR heating are available in the literature, particularly under IR heating followed by tempering and cooling (Abe & Afzal, 1997; Afzal & Abe, 1997). The theoretical prediction of moisture diffusivities is difficult, because of the variable physical and chemical structure and water content of each food product, as well as the drying conditions. Therefore, it is necessary to obtain these data through experimental procedures (Saravacos & Maroulis, 2001; Zhao, 1988). The evaluation of moisture diffusivity through drying experiments can be used with confidence for scaling up and optimizing design of IR driers. So, the objectives of this research were (1) to study moisture diffusivities during heating and cooling of rough rice with different initial moisture contents under various bed thicknesses, tempering and cooling treatments, and (2) to evaluate activation energy and moisture diffusivity coefficients of rough rice during IR heating and cooling.

2. Materials and methods

2.1. Preparation of rice samples

Freshly harvested medium grain rice, variety M202, obtained from Farmers' Rice Cooperative (West Sacramento, CA) was used for conducting the tests. The moisture content (MC) of rough rice was 33.8 ± 0.2 g moisture/100 g dry solid (high MC) at the harvest. The rice sample with the high MC was divided into three equal portions. In order to obtain samples with different initial moisture contents, two of the three portions were naturally dried to 31.2 ± 0.1 and 25.8 ± 0.2 g moisture/100 g dry solid at ambient temperature of 18 °C–20 °C on the floor in the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis. During drying the rice was mixed frequently to ensure uniform drying. It took about 18 and 45 h to reach the 31.2 and 25.8 g moisture/100 g dry solid, respectively. The portions at the three MCs were kept in sealed polyethylene bags at temperature of 5 ± 1 °C to ensure no additional moisture loss before the drying tests. At time of testing, each portion was further divided into 500 g samples with a sample divider (Boerne-sampler, Chicago, IL) at the test time. The reported moisture contents were in dry basis, db and determined by the air oven method (130 °C for 24 h) (ASAE, 1995).

2.2. 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. The IR dryer was comprised of two main components, IR emitter and drying bed. A catalytic emitter provided by Catalytic Industrial Group (Independence, Kansas) 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 650 °C with corresponding peak wavelength 3.1 μm, assuming the emitter is a blackbody. 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 tray, 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 due to shining surface for minimized the radiation energy loss through the drying tray. 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 drying tray surface to measure the bed temperature. The rice bed was located at 5 cm below the bottom edge of the wave guide with average IR intensity of 5348 W/m^2 at the rice bed surface. The radiation intensity was measured with an Ophir FL205A Thermal Excimer Absorber Head (Ophir, Washington, MA).

2.3. Drying procedures

The rice samples with different initial MCs were heated for six different time durations (15, 30, 40, 60, 90 and120 s) under IR radiation intensity of 5348 W/m^2. All tests were replicated three times at each condition. For the drying test, a 500 g rice sample was placed on the drying bed as single-layer (about 2 mm), 5 mm, and 10 mm with corresponding loading rates of 2.5, 4.5, and 6.5 kg/m^2, respectively. The initial drying bed temperature was 35 °C and rice was at ambient temperature for all drying tests.

2.4. Measurements of rice temperature and moisture removal

To determine drying characteristics and moisture diffusivities under different heating conditions, the rice temperature and moisture loss were measured at the end of each heating period. After IR heating, the rice temperature was measured using a Type T thermocouple - time constant 0.15 s - (Omega Engineering Inc. Stamford, CT) immediately after heated rice was collected into a container. The thermocouple was kept at the center of the rice mass until the temperature reading was stabilized, which normally took from 10 to 30 s. The average temperature of three replicates for each treatment is reported. The rice samples were weighted using 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 removal was calculated as the difference between the initial MC and the MC after treatment.

2.5. Tempering and cooling procedures

Tempering was conducted by keeping rice samples in closed containers placed in an incubator set at a temperature that was equal to the temperature of the rice after heating. Tempering of IR heated rice was carried out for 4 h immediately following the IR heating. After the tempering or non-tempering treatments, the samples were cooled using natural or forced air cooling at room temperature of 23 ± 1 °C as a thin layer (about 10 mm thick). For natural cooling, the rice samples were placed on a laboratory bench. Forced air cooling was achieved by using ambient air; the air velocity was 0.1 m/s which is similar to commercial drying practice. Air velocity was measured using a hot wire anemometer (Solomat MPM 500, UK) with an accuracy of 0.01 m/s. The cooling times were from 20 to 40 min for natural cooling and 5 min for forced air cooling. At the end of cooling, the sample temperatures were close to room temperature, and the temperature difference between the rice and the room air was less than 2 °C. Samples were weighed just prior to and after cooling. These data along with the calculated moisture contents after heating were used to calculate moisture removals during cooling.

2.6. Moisture diffusivity estimation

Rice moisture diffusivities were estimated by two approaches: the diffusion equation (Fick's law) method, and the slope method. The diffusivities obtained by the two approaches were then compared.

2.6.1. Diffusion equation

Fick's second law Eq. (1) was used to calculate the diffusivity (Crank, 1975, pp. 69–88)

$$\frac{\partial M}{\partial t} = \mathbf{D}\left[\frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r}\right] \tag{1}$$

Where M is moisture content (g moisture/100 g dry solid), D is moisture diffusivity (m^2/s) and r is the radius of a small sphere (m) from which moisture is diffusing. For simplicity we assumed that (1) paddy rice (medium grain) has a spherical shape with radius, r; (2) diffusivity is homogeneous throughout the whole rough rice kernel (endosperm, bran and hull); (3) moisture moves radically outward from inside the grain and through its surface; (4) shrinkage of the rice kernel during drying is negligible; and (5) mass transfer is symmetric and resistance to mass transfer at the surface of kernel is negligible. The initial condition considered in this study was that initial moisture is uniform throughout the rice kernel. With these assumptions, the solution of Eq. (1) is (Brooker, Bakker-Arkema, & Hall, 1992; Steffe, 1979; Steffe & Singh, 1982; Vagenas & Marinos-Kouris, 1991; Wang, 1978):

$$\mathrm{MR} = \frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2}\exp\left(-\frac{\pi^2 Dt}{r^2}\right) \tag{2}$$

Where MR is moisture ratio (dimensionless), M_0 is initial moisture content (g moisture/100 g dry solid), M is moisture content at a given time (g moisture/100 g dry solid), M_e is equilibrium moisture content (g moisture/100 g dry solid). Under infrared heating, t is average exposure time (s) and the equilibrium moisture content, M_e is considered to be zero (Fasina, Tyler, & Pickaw, 1998), and r is radius of rice kernel (m) which equals the distance in the radial direction from center to surface, so Eq. (2) reduces to:

$$\mathrm{MR} = \frac{M}{M_0} = \frac{6}{\pi^2}\exp\left(-\frac{\pi^2 Dt}{r^2}\right) \tag{3}$$

2.6.2. The slope method

The slope method (Saravacos & Raouzeos, 1984) was also used to estimate the moisture diffusivity. The experimental drying curve (MR versus heating time) was compared to the theoretical diffusivity curve (MR versus F_0). The slope of the experimental drying curve $(\mathrm{dMR/d}t)_{\mathrm{exp}}$ and the theoretical curve $(\mathrm{dMR/d}F_0)_{\mathrm{th}}$ were estimated at a given value of MR. The moisture diffusivity, D was estimated with the following equation (Karathanos, Villalobos, & Saravacos, 1990):

$$D = \frac{\left(\frac{\mathrm{dMR}}{\mathrm{d}t}\right)_{\mathrm{exp}}}{\left(\frac{\mathrm{dMR}}{\mathrm{d}F_0}\right)_{\mathrm{th}}} \times r^2 \tag{4}$$

Where D is moisture diffusivity (m^2/s), MR is moisture ratio (dimensionless), F_0 is Fourier number ($D\,t/r^2$) for diffusion and r is rice kernel radius (m).

2.7. Activation energy and coefficient of moisture diffusivity

The dependence of moisture diffusivity coefficient on rice temperature at different drying bed thicknesses, tempering and cooling treatments was represented by the Arrhenius equation:

$$D = D_0\exp\left(-\frac{E_a}{RT}\right) \tag{5}$$

The activation energy, E_a (kJ/mol), and moisture diffusivity coefficient, D_0 (m^2/s), were determined from the plot of ln(D) versus $1/T$, where T is the rice grain temperature (°C) at the end of heating or beginning of cooling. The slope of the line is ($-E_a/R$), where R is the gas constant, *8.314 kJ/mol K*, and the intercept equals to ln(D_0) (Barrozo, Souza, Costa, & Murata, 2001).

2.8. Statistical analysis

A multiple comparison procedure (Tukey test) was carried out using Sigma Stat software (Version 2.0, Jandel Corporation, San Rafael, CA), to compare rice moisture diffusivities for different temperatures, initial moisture contents and drying bed thicknesses.

3. Results and discussion

3.1. Rice temperature with different heating durations

In our previous publication, we have reported the detailed results of rice temperature change and moisture removal of rough rice harvested with three initial MCs during IR heating (radiation intensity of 5348 W/m^2) (Khir, Pan, Salim, & Thompson, 2007;). The moisture removal under natural and forced cooling, after tempering and non-tempering treatments, were also studied. The results indicated that rice temperature increased with increasing heating duration under the same drying bed thickness. The low MC rice samples rose to slightly higher temperatures than the high MC rice samples with the same heating duration, which is logical due to less energy being used for heating the water and a lower evaporative cooling effect in the low MC rice. However, the maximum difference in the temperatures of the samples with different initial MCs under the same heating duration and drying bed thickness was only 2.4 °C, which was relatively small.

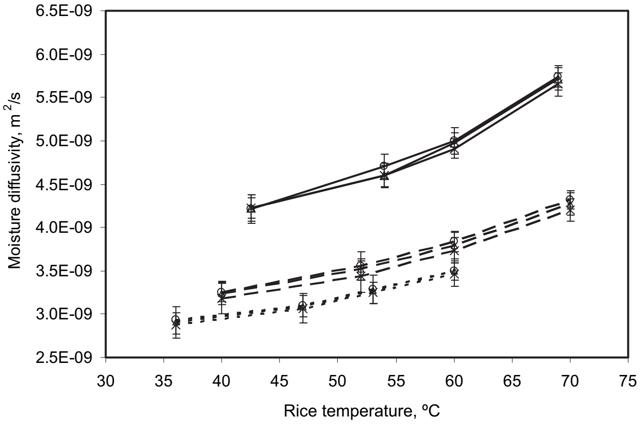

Fig. 1. Moisture diffusivities of rice samples under different temperatures, initial moisture contents and drying bed thicknesses. —✕—, IMC 25.8% single layer; —△—, IMC 31.2% single layer; —○—, IMC 33.8% single layer; —✕—, IMC 25.8% 5 mm; — △— -, IMC 31.2% 5 mm; —○—, IMC 33.8% 5 mm; -✕-, IMC 25.8% 10 mm; - - △ - - -, IMC 31.2% 10 mm; -○-, IMC 33.8% 10 mm.

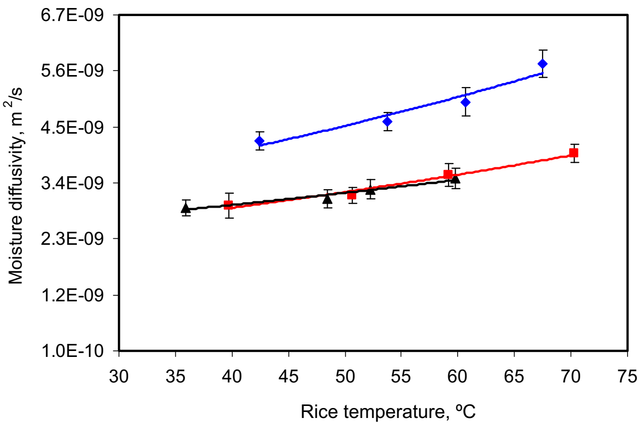

Fig. 2. Relationship between rice temperature and moisture diffusivity of rice with initial moisture content of 31.2 g moisture/100 g dry solid at different drying bed thicknesses. ◆, single layer, ($D_e = 2\text{E-}09e^{0.0118T}$ $R^2 = 0.94$); ■, 5 mm, ($D_e = 4\text{E-}10e^{0.0195T}$ $R^2 = 0.98$); ▲, 10 mm, ($D_e = 5\text{E-}10e^{0.0162T}$ $R^2 = 0.96$).

High heating rates and moisture removal were achieved under relatively short IR heating time with the tested drying bed thicknesses. For example, it took only 60, 90 and 120 s to achieve rice temperatures of approximately 60 °C and remove 2.0, 2.1, and 2.1 g moisture/100 g dry solid for the low MC rice and 2.6, 2.7, and 2.5 g moisture/100 g dry solid for high MC rice for the three bed thicknesses – single-layer, 5 mm and 10 mm – respectively, during heating alone. The corresponding total moisture removals, after tempering and natural cooling treatments, were 4.1, 4.0, and 3.8 g moisture/100 g dry solid and 6.1, 7.0, and 5.9 g moisture/100 g dry solid. The results also indicated that high rice milling quality was achieved by heating the rice to about 60 °C followed by tempering and natural cooling. These results are in agreement with those reported by Pan et al. (2008). They found that IR heating can be used for simultaneous drying and disinfestation of freshly harvested rough rice and the optimum conditions to achieve that are a 60 °C followed by tempering and natural cooling. It can be seen from these results that during IR heating high heating rate and a significant amount of moisture removal could be achieved for rice under IR heating during a short time. Also, after IR heating, tempering and cooling treatments improved moisture removal and rice quality. Therefore, it is important to investigate effect of the rice temperature, initial moisture content, tempering and cooling treatments on rice moisture diffusivity under IR heating at different drying bed thicknesses.

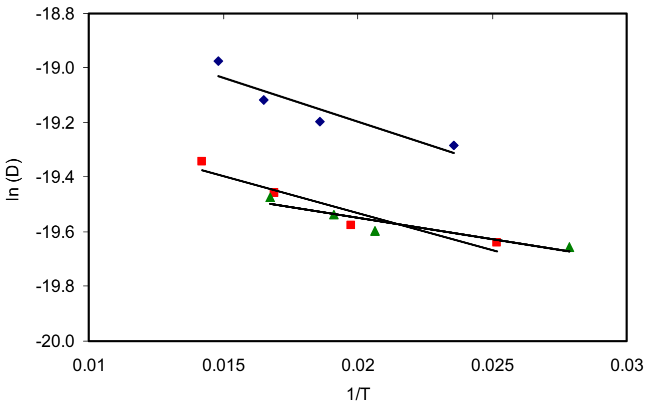

Fig. 3. Plot of the estimated ln (D) values versus 1/T at different drying bed thicknesses for rice with initial moisture content 31.2 g moisture/100 g dry solid. ◆, single layer ($R^2 = 0.86$); ■, 5 mm ($R^2 = 0.88$); ▲, 10 mm ($R^2 = 0.88$).

Table 1

Activation energy and moisture diffusivity coefficient for IR dried rice at different drying bed thicknesses and initial moisture of 31.2 g moisture/100 g dry solid.

Drying bed thickness	D_o, m^2/s	SD	E_a, kJ/mol	SD
Single-layer	9.20×10^{-9}	5.10×10^{-10}	265.2	07.0
5 mm	6.20×10^{-9}	3.90×10^{-10}	223.6	11.0
10 mm	4.60×10^{-9}	2.88×10^{-10}	128.0	08.0

Note: SD - standard deviation.

3.2. *Effect of temperature and initial MC on moisture diffusivity during heating*

Relationships between moisture diffusivity calculated with first approach and rice temperature with different initial MCs at drying bed thicknesses of single-layer, 5 mm and 10 mm are shown in Fig. 1. It is clear that moisture diffusivity under IR drying increases with the increase of rice temperature under the same drying bed thickness. For example, at the rice temperature of 42.5 °C the moisture diffusivity values were 4.23×10^{-9}, 4.23×10^{-9} and 4.22×10^{-9} m^2/s for rice with initial MCs of 25.8, 31.2 and 33.8 g moisture/100 g dry solid, respectively, for single-layer drying. When the rice temperature increased to 60 °C, the corresponding moisture diffusivity values reached to 4.91×10^{-9}, 4.97×10^{-9} and 5.00×10^{-9} m^2/s. For drying bed thickness of 10 mm the moisture diffusivity values were 3.06×10^{-9}, 3.09×10^{-9} and 3.10×10^{-9} m^2/s at rice temperature of 47 °C for rice with initial MCs of 25.8, 31.2 and 33.8 g moisture/100 g dry solid, respectively, and 3.46×10^{-9}, 3.49×10^{-9} and 3.5×10^{-9} m^2/s at rice temperature of 60 °C. A similar trend was observed when the drying was conducted at the rice bed of 5 mm. A Tukey test was applied to compare the moisture diffusivities of rice samples with different initial MCs at the same temperature and drying bed thickness. The results showed there was no significant effect of initial MC ($P < 0.05$). The results also revealed that the moisture diffusivity was affected only by rice temperature and drying bed thickness. Therefore, the effect of drying bed thickness, tempering and cooling methods on moisture diffusivity of rice at one initial MC level is discussed to illustrate the drying characteristics.

In general, it is clear that the moisture diffusivity of rice under IR drying strongly depends on rice temperature which in agreement with results reported by Steffe and Singh (1982) for rough rice (medium grain variety) under convective hot air drying. It can be

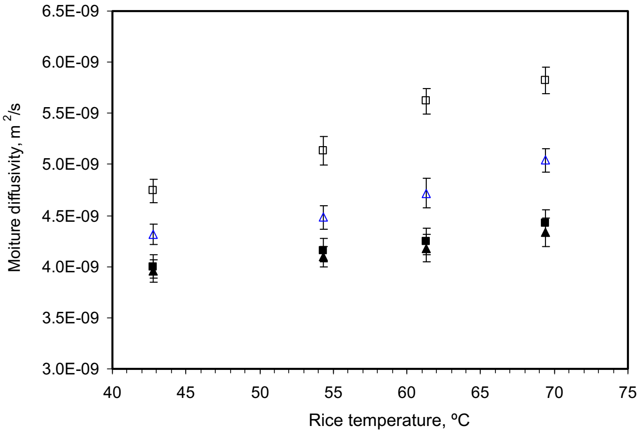

Fig. 4. Moisture diffusivity of rice with initial moisture content of 31.2 g moisture/100 g dry solid under different cooling methods with and without tempering. Δ, tempering followed by natural air cooling; □, tempering followed by forced air cooling; ▲, no tempering followed by natural air cooling; ■, no tempering followed by forced air cooling.

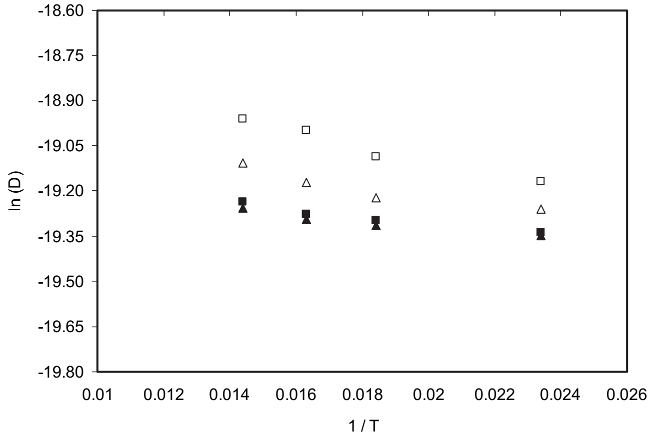

Fig. 5. Plot of the estimated ln (D) values versus $1/T$ at different tempering and cooling treatments for rice with initial moisture of 31.2 g moisture/100 g dry solid. Δ, tempering followed by natural air cooling; □, tempering followed by forced air cooling; ▲, no tempering followed by natural air cooling; ■, no tempering followed by forced air cooling.

seen from above results that under IR heating the rice temperature has a pronounced influence on rice moisture diffusivity. As a result, the increase of rice temperature resulted in the increase of moisture diffusion rate through rice kernels. Therefore, high heating and drying rates could be achieved under IR heating within a short time.

3.3. *Effect of drying bed thickness on moisture diffusivity during heating period*

The relationships between rice temperature and moisture diffusivity for rice with initial MCs of 31.2 g moisture/100 g dry solid at different drying bed thicknesses are shown in Fig. 2. The high correlation between the rice temperature and rice moisture diffusivity under different drying bed thicknesses was obtained with exponential models. The models could be used to predict the moisture diffusivity change for rice with a known rice temperature under the tested drying bed thicknesses.

The moisture diffusivity for single-layer drying was much higher than that at drying bed thicknesses of 5 mm and 10 mm. The high moisture diffusivity is related to higher moisture diffusivity coefficient and effective activation energy (Fig. 3 and Table 1). For example, the moisture diffusivity coefficient values were 9.2×10^{-9}, 6.2×10^{-9} and 4.6×10^{-9} m^2/s for drying bed thicknesses of single-layer, 5 mm and 10 mm, respectively. The corresponding activation energy values were 265.2, 223.6 and 128.0 kJ/mol. The higher moisture diffusivity coefficient and activation energy at single-layer drying bed thickness may due to uniform heating and higher heating rate compared to those at drying bed thickness of 5 mm and 10 mm. Uniform heating provided by IR may increases the activation energy of water molecules resulting in increased mobility of moisture diffusion. For example, it took 20, 40, and 60 s to reach to about 45 °C rice temperature for drying bed thicknesses of single-layer, 5 mm and 10 mm, respectively. The corresponding moisture diffusivities were 4.2×10^{-9}, 3.18×10^{-9} and 2.9×10^{-9} m^2/s. Similarly, it took 60, 90 and 120 s to reach to 60 °C rice temperature for drying bed thicknesses of single-layer, 5 mm and 10 mm, respectively. The corresponding moisture diffusivities were 4.91×10^{-9}, 3.55×10^{-9} and 3.40×10^{-9} m^2/s.

The moisture diffusivities of rice under IR heating with the tested drying bed thicknesses were high compared to those for convective drying. For example, moisture diffusivity of rough rice with convective drying at an air temperature of 45 °C was 8.3×10^{-12} m^2/s (Steffe & Singh, 1982). This means that high heating and drying rate could be achieved during IR rice drying with drying bed thicknesses of up to 10 mm.

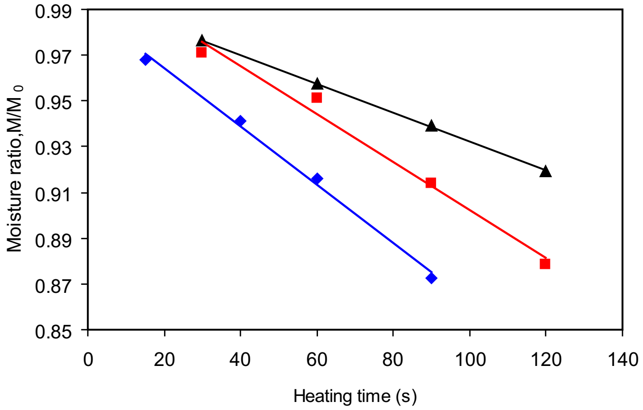

Fig. 6. Plot of the moisture ratio values versus heating time at different drying bed thicknesses and initial moisture content of 31.2 g moisture/100 g dry solid. ◆, single layer; ■, 5 mm; ▲, 10 mm.

Table 2
Average values of activation energy and moisture diffusivity coefficient of rice with initial moisture content of 31.2 g moisture/100 g dry solid during cooling under different tempering and cooling treatments.

Tempering	Cooling method	D_o, m^2/s	SD	E_a, kJ/mol	SD
Yes	Forced air	8.36×10^{-9}	3.77×10^{-10}	194.5	6.23
Yes	Natural air	6.25×10^{-9}	2.90×10^{-10}	133.0	4.89
No	Forced air	5.12×10^{-9}	1.89×10^{-10}	88.1	3.97
No	Natural air	4.92×10^{-9}	1.66×10^{-10}	78.1	3.11

Note: SD - standard deviation.

3.4. *Moisture diffusivity during cooling*

As an example, the clear trends of rice moisture diffusivity with initial MCs of 31.2 g moisture/100 g dry solid during cooling under tempering vs. non-tempering and natural air cooling vs. forced air cooling treatments are seen in Fig. 4. The moisture diffusivities of tempered rice samples under natural air cooling and forced air cooling were 4.3×10^{-9}–5.0×10^{-9} m^2/s and 4.7×10^{-9}–5.8×10^{-9} m^2/s respectively. In contrast, moisture diffusivities of the non-tempered

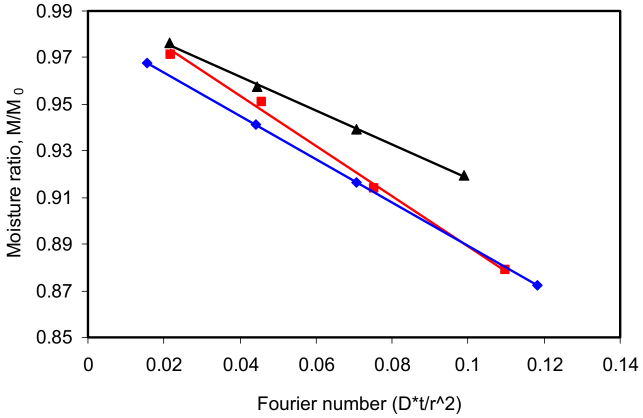

Fig. 7. Plot of the moisture ratio values versus Fourier number at different drying bed thicknesses. ◆, single layer ($R^2 = 0.98$); ■, 5 mm ($R^2 = 0.97$); ▲, 10 mm ($R^2 = 0.98$).

Table 3
Moisture diffusivity values estimated by diffusion equation and slope method for rice with initial moisture content of 31.2 g moisture/100 g dry solid.

Drying bed thickness	Moisture diffusivity average, m^2/s			
T & NT	Diffusion equation	SD	Slope method	SD
Single-layer	4.78×10^{-9}	6.30×10^{-10}	4.81×10^{-9}	6.33×10^{-10}
5 mm	3.71×10^{-9}	4.30×10^{-10}	3.78×10^{-9}	4.29×10^{-10}
10 mm	3.51×10^{-9}	2.51×10^{-10}	3.57×10^{-9}	2.53×10^{-10}
T-SC	4.65×10^{-9}	3.10×10^{-10}	4.71×10^{-9}	3.20×10^{-10}
NT-SC	4.15×10^{-9}	1.50×10^{-10}	4.18×10^{-9}	1.48×10^{-10}
T-FAC	5.30×10^{-9}	4.80×10^{-10}	4.71×10^{-9}	4.78×10^{-10}
NT-FAC	4.20×10^{-9}	1.70×10^{-10}	4.18×10^{-9}	1.71×10^{-10}

Note: T - tempering, FAC – forced air cooling, NT - non-tempering, SC – natural air cooling, SD - standard deviation.

rice were 4.0×10^{-9}–4.3×10^{-9} m^2/s and 4.0×10^{-9}–4.4×10^{-9} m^2/s under natural and forced air cooling respectively. The tempered rice samples had higher moisture diffusivity than the non-tempered rice samples, which showed the importance of tempering in IR rice drying for maximum amount MC removal during cooling and may also have a positive effect on milling quality. Forced air cooling produced higher moisture diffusivity than natural cooling in the tested temperature range, although too much moisture removal may cause rice fissures, lowering rice milling quality which was reported in different publications.

The above data indicate that the tempering process reduced the moisture gradient in rice kernels and allowed the moisture to equilibrate before the rice kernels were cooled. As a result, moisture diffusivity coefficient increased with tempering compared to non-tempering treatment as shown in (Fig. 5 and Table 2). Therefore, the tempering process is a critical step to increase the moisture diffusivity and improve 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 too much moisture removal may cause rice fissures lowering rice milling quality, which needs to be considered (Pan et al., 2008). A high moisture removal could be achieved with a combination of tempering and natural cooling without affecting rice quality and needing additional energy input.

3.5. *Diffusivities calculated with the slope method*

For IR heating period, the experimental drying curves which represent the relationship between the moisture ratio and heating time with different drying bed thicknesses are shown in Fig. 6. The approximate D values, obtained using the Fick's Law, were used as diffusivity values for plotting the theoretical curves (dMR versus Fourier number) of Fig. 7. The moisture diffusivity values obtained by both Fick's Law and the slope method are presented in Table 3. In general, there is no significant difference between the moisture diffusivity values obtained by the diffusion equation and the slope method. Even though, the moisture diffusivity values obtained by the slope method were slightly higher than those from the diffusion equation. For cooling, the moisture diffusivity values obtained from the slope method for tempering and non-tempering are parallel to those obtained with Fick's Law.

4. Conclusions

The research shows that high moisture diffusivity for rice drying can be achieved within a relatively short heating time by using IR heating. Both rice temperature and drying bed thickness had significant influence on rice moisture diffusivity. Rice moisture diffusivity under IR heating was not significantly affected by initial MCs in the tested range. The rice moisture diffusivity had a positive relationship with rice temperature. Tempering after rapid IR heating is essential to achieve a high rice moisture diffusivity coefficient and improve moisture removal during cooling. Therefore, significant amount of moisture can be removed without additional energy consumption during cooling.

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