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Drying kinetics of glutinous rice using an infrared irradiation technique

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Abstract

This study investigates the drying kinetics of glutinous rice using an infrared irradiation technique. The glutinous rice was dried at three infrared irradiation powers, 300, 400 and 500 W, with three thicknesses, 5, 10 and 15 mm. The glutinous rice was dried starting from an initial moisture content of 81% (wb) down to a final moisture content of 25% (wb). The results indicate that the drying kinetics depended on the drying temperature. The glutinous rice after drying at 300 W appeared lightest, while drying with the highest power, 500 W, it appeared darkest in color. Additionally, a layer thickness of 5 mm is accepable in the market and had the shortest time for drying, 104 to 194 minutes. The moisture ratio was fitted to determine the model parameters that can adequately describe the drying kinetics. The regression analysis results showed that the Page model was the best model based on its highest value of $R^2$and its lowest values of χ^2 and $RMSE$. The moisture diffusivity of glutinous rice was found to be in the range of 32.96 to 53.26 $x10^{-9}$ m²/s.

Keywords: Irradiation, Drying kinetics, Sticky rice, Moisture, Diffusivity, Activation energy

1. Introduction

Dried glutinous rice is a main ingredient used to produce Khao Tan, i.e., rice crackers. This food has a crispness and sweetness from brown sugar to give a naturally delicious flavor. They go well with porridge, rice soup, milk, tea, coffee or snacks anytime. Their initial moisture content is very high and can be reduced by drying in sunlight for 2 to 3 days. Duting this time, they may be contaminated with dust, dirt, rain, by animals, birds, rodents, insects and microorganisms [1]. Various mechanisms influence the operating costs, drying times and quality of products [2]. Conduction and convective heat transfer have primarily been used, while radiant heat transfer at short wavelengths, such as sunlight and an infrared lamps, have also been tried [3].

Infrared radiation techniques are widely used in food industries for heating and drying purposes [4]. In food processing, far infrared radiation (FIR) heaters are used more than the near infrared radiation (NIR) because high energy damages foods [5]. Furthermore, energy is more efficiently absorbed in the FIR wavelength range. The application of FIR in the food industry can be classified into four major areas based on different applications: cooking [6], drying [7], heating [8] and pasteurization [9]. In the current work, the focus was on the drying. Matsuoka studied the drying characteristics of rough rice during FIR heating in forced-air and vacuum drying [10]. His results showed that FIR with forced-air drying resulted in the least loss of chlorophyll since the drying time was reduced. The heat is supplied as electromagnetic radiation. This technique has been adapted for drying agricultural products such as soybeans and paddy rice, which are solids [11]. Reports about the drying kinetics of glutinous rice using infrared technology are scarce.

The objectives of this research were (i) to experimentally study the drying kinetics of glutinous rice in an infrared dryer, and, (ii) to develop mathematical drying models.

2. Materials and methods

2.1 Glutinous rice

Glutinous rice was cooked by steaming and formed it into slabs with layer thicknesses of 5, 10 and 15 mm, as shown in Figure 1. It was allowed to cool to a temperature of 30°C. Weights were measured using an electronic balance with an accuracy of ± 0.1 g.

The moisture content of the steamed glutinous rice was determined using a standard method (AOAC 930.15) [12] which used Eq. (1):

$$M_{in} = \left(\frac{m_w - m_d}{m_w}\right) 100\% \quad (1)$$

where, m_w is the wet weight, m_d is the dry weight and M_{in} is the moisture content on a wet basis. The average

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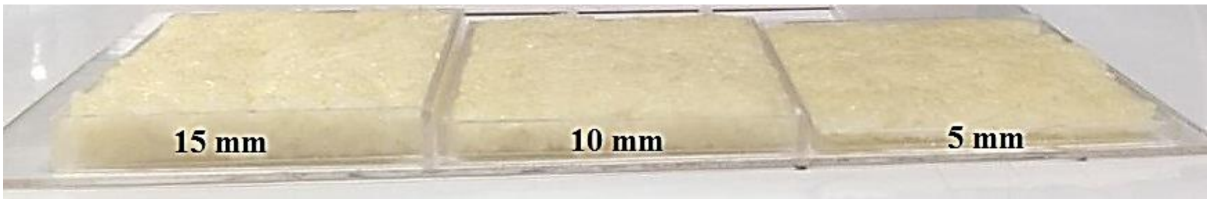


Figure 1 Samples of glutinous rice after steaming and forming

initial moisture content of the steamed glutinous rice was around 0.81 or 81% on a wet basis (wb).

2.2 Moisture diffusivity

Mmoisture diffusivity , D, is imporant in mass transfer. The moisture movement inside the food was calculated using Fick's second law as Eq. (2). Diffusivity is an important transport property needed in calculations and modeling of food drying based on the following assumptions. Moisture is transferred internally to the surface and evaporation occurs at the surface. All glutinous rice grains are the same size and their physical properties are constant with time. The initial temperature and moisture content of all glutinous rice grains are the same and diffusion coefficient is constant [13].

$$\frac{\partial M}{\partial t} = D\,\nabla^2 M \quad (2)$$

The solution to Eq. (2) for an infinite slab has been presented by Crank [14] as Eq. (3):

$$MR = \frac{M_t - M_e}{M_{in} - M_e} = \frac{8}{\pi^2}\sum_{n=0}\frac{1}{(2n+1)^2}\,exp\left[\frac{-(2n+1)^2\pi^2 D}{L^2}\right]t \quad (3)$$

where, MR is the dimensionless moisture ratio, M_t is the average moisture content of wet material at any time, M_{in} is the initial moisture content, M_e is the equilibrium moisture content, D is the moisture diffusivity and L is the thickness of the material. Since the values of M_e are relatively small compared with M_{in} and M_t, the empirical moisture ratio can be simplified as Eq. (4):

$$MR = \frac{M_t}{M_{in}} \quad (4)$$

For investigating the moisture diffusivity (D), Eq. (3) can be written in logarithmic form as Eq. (5):

$$\ln MR = \left(ln\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D}{L^2}\right)t \quad (5)$$

The temperature effects are modeled using an Arrhenius type relationship as Eq. (6):

$$D = D_o exp\left(-\frac{E_a}{RT}\right) \quad (6)$$

where D_o is the pre-exponential term, E_a is the activation energy for moisture diffusion, R is the ideal gas constant and T is the absolute temperature of the glutinous rice surface. The popular drying models in Table 1 were used for modeling glutinous rice drying. The best model for describing the drying characteristics of glutinous rice was chosen as the one with the lowest reduced values of Chi-square(χ^2), root mean square error (RSME) and highest coefficient of determination (R^2). These were used to compare the categorical responses between the experimentally determined moisture ratios $(MR_{exp,i})$ and the predicted moisture ratios $(MR_{pre,i})$.

Regression analysis was performed using SPSS. The statistical parameters, χ^2 and RSME, were calculated using Eq. (7) and Eq. (8):

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-p} \quad (7)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right]^{1/2} \quad (8)$$

where N is the number of observations and p is the number of constants. Analysis of variance was done to find the effects of the applied microwave power.

Table 1 Well-known mathematical models of drying kinetics [3]

No	Model name	Equation
1	Newton	$MR = exp(-kt)$
2	Page	$MR = exp(-kt^n)$
3	Henderson and Pabis	$MR = aexp(-kt)$
4	Logarithmic	$MR = aexp(-kt) + b$
5	Wang and Singh	$MR = 1 + at + bt^2$

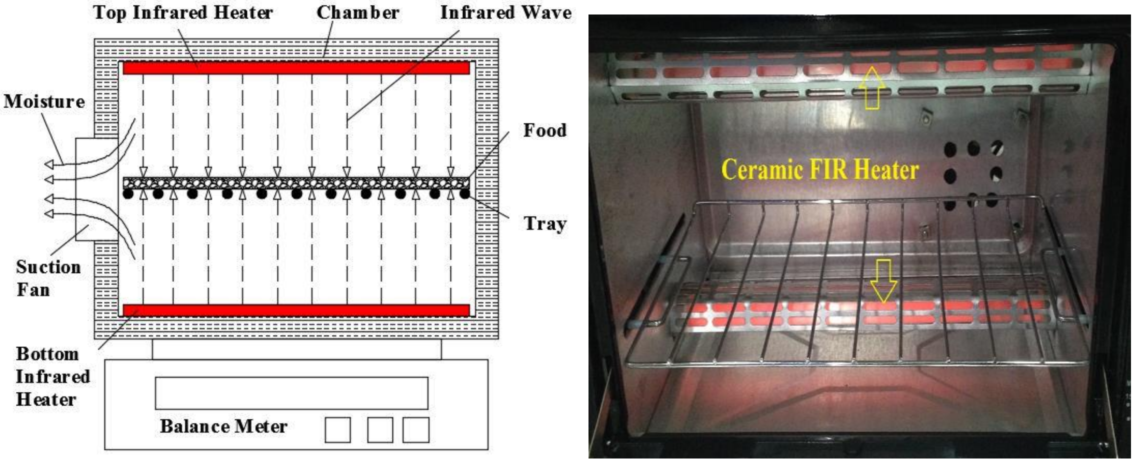
Note: MR is the moisture ratio, a, b, k and n are model constants and t is the drying time in minutes.

2.3 Infrared heating

Infrared energy is an electromagnetic energy that is transmitted as a wave the contacts a material and then is converted to heat [15]. It is classified as having three wavelength regions, near-infrared (0.78 to 1.4 μm), mid-infrared (1.4 to 3 μm) and far-infrared (3 to 1000 μm). The far-infrared radiation (FIR) usually means irradiative heating at wavelengths of 2.5 to 30 μm. As the temperature of the heater is raised, the amount of radiant energy delivered to the food increases and the peak wavelength decreases. The FIR heater used in this research was controlled using a variable resistor and measured using a Watt meter.

2.4 Experimental drying setup

An apparatus was constructed using infrared drying equipment at the Faculty of Engineering, Burapha University, Thailand, as shown in Figure 2a. It consisted of an FIR heater, as shown in Figure 2b, with variable power output from 300 - 500 W, which was measured by a Watt meter with an accuracy of ± 0.1 W. For measuring drying kinetics, moisture was removed using a 50 W fan. The FIR heaters were fixed over and beneath the food. The surface



(a) (b)

Figure 2 Schematic diagram of an infrared dryer (a) and drying chamber (b)

temperature of the food was measured using an infrared thermometer with an accuracy of ± 0.1 °C.

Glutinous rice was cooked by steaming and form ed into slabs of three thicknesses, 5, 10 and 15 mm, all with 10 cm x 10 cm of top and bottom surface areas. The experimental conditions were set at three infrared powers: 300, 400 and 500 W. The dryer was run until the temperature reached steady state, which normally took 30 min. A three digit balance with an accuracy of ± 0.001g was installed at the bottom of the drying chamber. The difference between the initial and final weights was used to calculate the moisture loss of the glutinous rice. The experiments with done in triplicate and the data averaged.

3. Results and discussion

3.1 Drying results

The moisture ratios (MR) were calculated using Eq. (4) and plotted versus drying time in Figure 3.

Figure 3 shows moisture ratio and drying time at various infrared powers, 300, 400 and 500 W and three layer thicknesses, 5 mm (Figure 3a) 10 mm (Figure 3b) and 15 mm (Figure 3c). The surface temperatures of glutinous rice increased to 45, 48 and 51°C with increasing the infrared power from 300, 400 and 500 W, respectively. During the constant rate drying period, the surface temperature of the rice would approach the wet bulb temperature. During the falling rate period, the surface temperature would rise. The trends of the graphs under all conditions were exponential in nature. The required times for drying the glutinous rice from initial moisture of 81% (wb) to a final moisture of 25% (wb) ranged from 104 to 194 minutes as shown in Table 2.

Table 2 Drying times in minutes at different power levels and surface temperatures

Thickness (mm)	Drying times (minutes)		
	300 W, 45°C	400 W, 48°C	500 W, 51°C
5	104	134	166
10	121	151	182
15	136	163	194

3.2 Drying discussion

Heat was applied to glutinous rice by electromagnetic radiation from an infrared heater. The energy emitted from the heater passed through air and was absorbed by the rice. The high temperatures used for drying can cause both physical and chemical changes on the products. The experimental results (Figure 3) also illustrate that the left is the constant rate period and to the right is the falling rate period [16].

Layer thickness also affected the drying time (Table 2) because the abundance of free water on the surface of the glutinous rice contributed to moisture liberation. A layer thickness of 5 mm is accepable in the market and had the shortest drying time, which is important for producing Khao Tan (rice crackers).

A comparison of the color of the 5 mm thickness of glutinous rice after drying at three irradiation power levels, i.e., 300, 400 and 500 W, is shown in Figure 4. The dried glutinous rice after drying with 300 W was lightest, while that dried at 500 W was the darkest.

3.3 Drying models

The moisture ratios (MR) of glutinous rice at three infrared irradiation power levels, 300, 400 and 500 W, were statistically fitted to investigate the parameters of the drying models in Table 1. The parameter, T, the absolute temperature of glutinous rice surface, ranged from 318-324 K. The parameters of the drying models were investigated using SPSS based on the relationship of MR and drying time (t). The regression analysis results are shown in Table 3, indicating that the Page model was the best based on its highest value of $R^2$and lowest values of X^2 and $RMSE$.

3.4 Moisture diffusivity

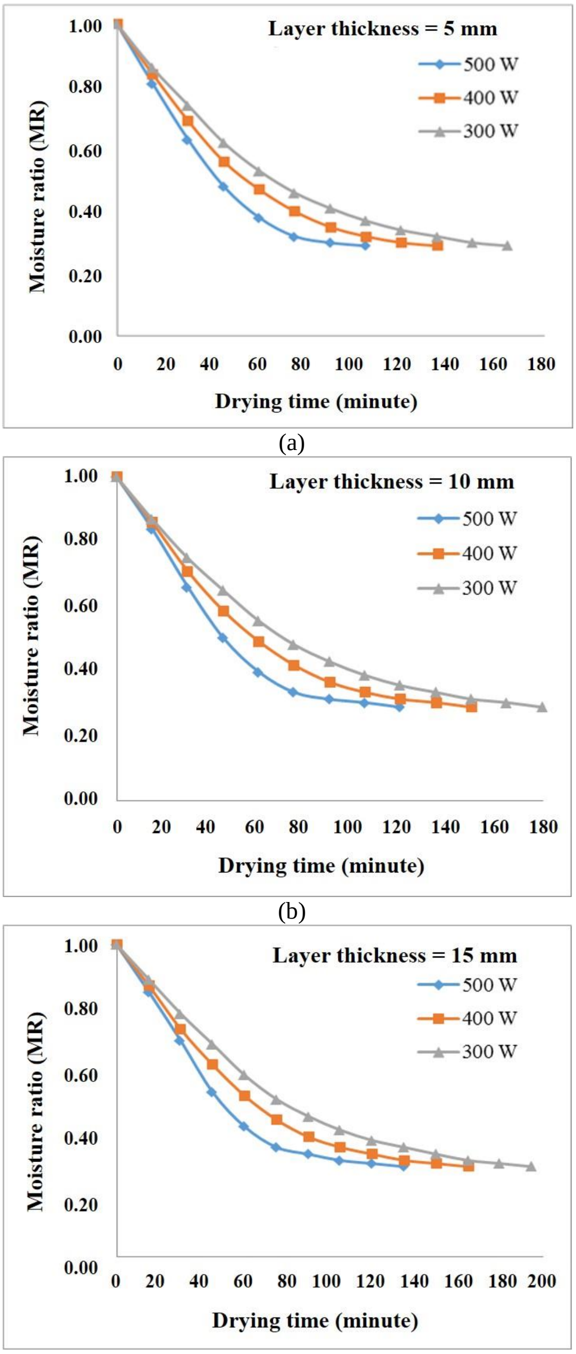
Moisture diffusivity (D) is a parameter that is proportional to internal transport of moisture within a material. Eq. (4) is written in a logarithmic form to determine the slopes derived from the linear regression of $lnMR$ against drying time (t) with R^2 values ranging from 0.81-0.9, as shown in Figure 5.

These results allowed determination of the moisture diffusivity of glutinous rice as seen in Table 4.

Table 3 Parameters of drying models in **Table 1**

No.	Model name	Parameters of Model	R^2	χ^2	$RMSE$
1	Newton	$k = 0.00041T - 0.0126$	0.978	0.00135	0.032712
2	Page	$k = 0.00032T - 0.0143$ $n = -0.00614T + 1.7128$	0.998	0.00027	0.002233
3	Henderson and Pabis	$k = 0.00042T - 0.0114$ $a = -0.00122T + 1.1568$	0.985	0.00137	0.021631
4	Logarithmic	$k = 0.00059T - 0.0252$ $a = -0.01213T + 2.0267$ $b = 0.01231T - 0.9934$	0.991	0.00063	0.013955
5	Wang and Singh	$a = -0.00031T + 0.0822$ $b = 0.00012T - 0.0091$	0.995	0.00176	0.007559

Note: T is surface temperature of glutinous rice at 45 – 51 °C and 5 mm thickness.



(a)

(b)

(c)

Figure 3 Relation of moisture ratio to drying time

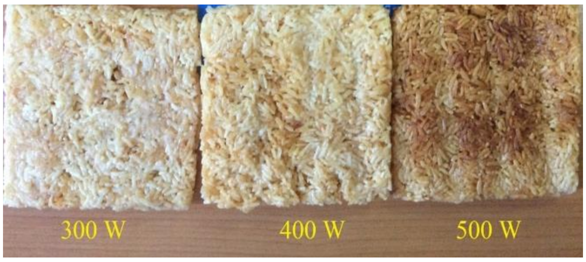


Figure 4 Color of glutinous rice (5 mm thickness) after drying at three radiation power levels

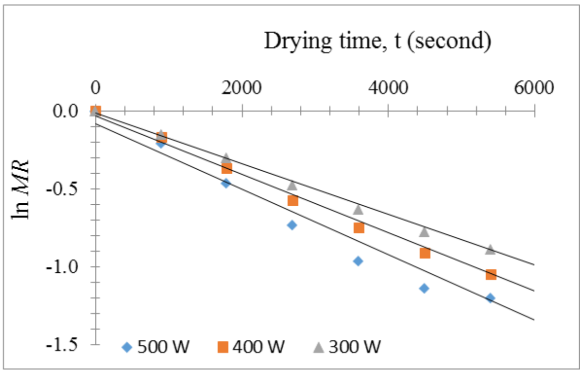


Figure 5 $lnMR$ versus drying time (t) of glutinous rice (5 mm thickness) at 3 infrared power levels

Table 4 Moisture diffusivity of 5 mm thick glutinous rice

Infrared Power (W)	Abs. temperature (K)	$D \times 10^9$ (m²/s)
300	318	32.96
400	321	40.58
500	324	53.26

4. Conclusions

An infrared irradiation dryer was designed, constructed and operated at power levels of 300-500 W. Glutinous rice was dried at three thicknesses, 5, 10 and 15 mm. This rice, initially at 81% moisture (wb) was dried to a final moisture content of 25% (wb) with drying times ranging from 104 to 194 minutes. The surface temperatures of the glutinous rice increased from 45 to 51°C after increasing the infrared power from 300 to 500 W. Increasing the infrared power from 300 to 500 W decreased the drying time by 46.4%. At 300 W, the dried glutinous rice appeared lighter in color. Drying at the highest power, 500 W, produced the darkest product. A layer thickness of 5 mm is accepable for the market and had the shortest time for drying. The moisture ratio curves showed that internal moisture diffusion is the predominant resistance to drying. The moisture ratio curves were fitted to determine the parameters of models that can adequately describe their drying kinetics. The regression analysis results showed that the Page model was the best model based on its highest value of $R^2$and lowest values of χ^2 and $RMSE$ compared with the other models. The moisture diffusivity of glutinous rice was found to be in the range 32.96 to 53.26 $x10^{-9}$ m²/s.

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