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Modelling of intermittent drying of thin layer rough rice

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Abstract

Various mathematical models in describing the intermittent drying characteristics of thin layer rough rice were investigated. Experimental values for drying temperature 40 °C, drying velocity 1.5 ms^{-1} and tempering period ranging from 0 h to 1 h were fitted to the theoretical models to relate the parameters of the drying models with the drying conditions. Suitability of fitting of the experimental data by models was specified as comparing the correlation coefficient, standard error and mean square deviation. The Midilli model was found to be the most adequate model in describing the intermittent drying of thin layer rough rice. The coefficient a and b, drying coefficient k and exponent n in the Midilli model can be expressed as a polynomial function of tempering time.

Keywords: Intermittent drying; Rough rice; Single layer; Drying model; Moisture ratio

1. Introduction

Moisture content is one of the most important factors affecting the quality of rough rice during storage and it is at a high level at the time of the harvest and must be reduced to nearly 14% (d.b.) with an appropriate drying process. Dryers used in the drying of rough rice usually utilize forced convection of warm air and drying process traditionally employs continuous drying at the same air temperature for moisture removal. The continuous drying characteristics of the rough rice have been investigated by many researchers and empirical or semi-empirical correlations for the prediction of drying rate have been performed with more or less success. Most of the mathematical models used in the studies dealing with the thin layer drying are given in Table 1. Henderson and Perry (1976) used Newton model in Table 1 to simulate the thin layer drying of rough rice and found that it is suitable in describing the rice drying except for the first two hours. Agrawal and Singh (1977) adopted the logarithmic model to simulate thin layer drying of short grain rough rice. Wang and Singh (1978) performed a regression analysis for various models on their single layer drying data for rough rice and suggested the quadratic equation given in Table 1. Sharma, Kunze, and Tolley (1982) suggested the two-term exponential model for thin layer drying of medium grain rough rice. Chen and Tsao (1994) used their experimental data to fit the Newton, Page, two-term exponential and Wang and Singh models in Table 1 and found that two term exponential model is the best fit among them. Four different thin-layer drying models were used by Chen and Wu (2001) to simulate thin layer drying of rough rice with high moisture ratio. Two-term exponential model was found as the best fit in this study. Abe and Afzal (1997) used various mathematical models in describing the thin layer drying characteristics of rough rice under natural convection and infrared radiation and found that the Page model is the most adequate among them. Basunia and Abe (2001) used the Page model to simulate the rough rice drying under natural convection and obtained a good fit for the moisture content. Basunia and Abe (2005) found that the Page model gives a very good fit for the moisture content for their drying data of medium grain rough rice. Das, Das, and Bal (2004) showed that the Page model

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Nomenclature

a	drying constant
b	drying constant
e_s	standard error
k	drying coefficient (h^{-1})
M	moisture content
MR	dimensionless moisture ratio
N	number of observations
N_c	number of constants in drying model
n	exponent
r	correlation coefficient
T	temperature (°C)
t	time (h)

Greek letters

χ^2	mean squared deviation
φ	relative humidity
τ	tempering time

Subscripts

e	equilibrium condition
o	initial condition
exp	experimental
pre	predicted

Table 1
Thin-layer drying models

Name	Model equation	References
Newton	$MR = \exp(-kt)$	O'Callaghan et al. (1971)
Page	$MR = \exp(-kt^n)$	Agrawal and Singh (1977)
Henderson and Pabis	$MR = a\exp(-kt)$	Chhinman (1984)
Logarithmic	$MR = a_0 + a\exp(-kt)$	Chandra and Singh (1995)
Logistic	$MR = a_0/1 + a\exp(kt)$	Chandra and Singh (1995)
Two-term exponential	$MR = a_1\exp(-k_1t) + a_2\exp(-k_2t)$	Henderson (1974)
Geometric	$MR = at^{-n}$	Chandra and Singh (1995)
Wang and Singh	$MR = 1 + a_1t + a_2t^2$	Wang and Singh (1978)
Midilli	$MR = a\exp(-kt^n) + bt$	Midilli et al. (2002)
Diffusion approach	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Kassem (1998)

describes the experimental data adequately on drying of high moisture rough rice in a vibratory infrared radiation dryer.

Intermittent drying is an alternative drying method and offers some advantages over continuous form of drying. Drying produces moisture gradients within the grain, which decreases the drying rate. However, a tempering period allows moisture within grain to diffuse to the external surface, thereby decreasing the moisture gradients. The thermal efficiency of such process is higher, because the thermal energy requirement reduces. An overview on intermittent drying of bio-products was given by Chua, Mujumdar, and Chou (2003) with selected results from experiments and mathematical models for a variety of biomaterials dried in a wide assortment of dryers. Chen (1998) and Shei and Chen (1998) used the Newton model to simulate the intermittent drying behavior of rough rice in a re-circulating type rice dryer. Residual analysis showed that the proposed predictors are quite adequate. Shei and Chen (1999) fitted four drying models to their experimental data of intermittent drying of rough rice and concluded that the Page, two-term exponential and Wang and Singh models were suitable thin layer equations for predicting deep-bed re-circulating rice drying while the Newton model was not adequate at the beginning of the drying period.

Mathematical modeling of thin layer drying is important for optimization of operating parameters and performance improvements of the drying systems. The main advantage of empirical or semi-empirical models in drying simulations is easy to apply. A lot of study has been made on modeling of continuous drying of rough rice as compared with those for intermittent drying. In this study, alternative mathematical models to simulate the intermittent drying curves of thin layer rough rice were evaluated and best fit was found using statistical analysis.

2. Mathematical formulation

Ten different moisture ratio equations given in Table 1 was taken into account for the purpose of specifying the most adequate model in intermittent drying simulation of thin layer rough rice.

The moisture ratio is defined as follows:

$$MR = \frac{M - M_e}{M_o - M_e} \tag{1}$$

Here M, M_o, M_e are the instantaneous, initial and equilibrium moisture contents, respectively.

The coefficient of correlation (r) was one of the primary criteria for selecting the best equation. In addition to

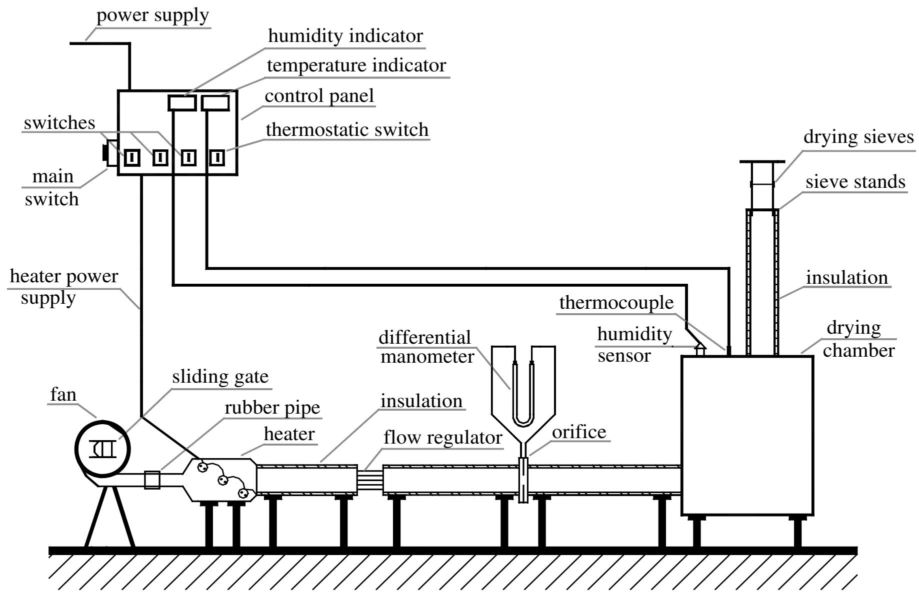

Fig. 1. A schematic view of the experimental set-up.

Table 2
Initial moisture ratios for rough rice

$T = 40$ °C, $\varphi = 0.220$, $M_e = 0.072$			
τ (h)	0	0.5	1
M_o	0.242	0.241	0.241

Table 3
Statistical analysis of the models for the tempering time $\tau = 0$

Model	Parameter	Value	Correlation coeff. (r)	Standart error (e_s)	Mean square of deviation (χ^2)
Newton	Drying coefficient, k	0.284	0.9877	0.0581	3.638×10^{-3}
Page	Drying coefficient, k	0.421	0.9997	0.0056	0.360×10^{-4}
	Exponent, n	0.669			
Henderson and Pabis	Drying coefficient, k	0.246	0.9835	0.0413	1.992×10^{-3}
	Coefficient, a	0.902			
Logarithmic	Drying coefficient, k	0.486	0.9972	0.0167	3.560×10^{-4}
	Coefficient, a_0	0.227			
	Coefficient, a	0.734			
Logistic	Drying coefficient, k	0.091	0.9967	0.0186	4.420×10^{-4}
	Coefficient, a_0	−0.300			
	Coefficient, a	−1.314			
Two-term exponential	Coefficient, a_1	0.355	0.9989	0.0107	1.589×10^{-4}
	Drying coefficient, k_1	1.088			
	Coefficient, a_2	0.626			
	Drying coefficient, k_2	0.152			
Geometric	Coefficient, a	0.489	0.8193	0.1289	1.938×10^{-2}
	Exponent, n	0.116			
Wang and Singh	Coefficient, a_1	−0.297	0.9866	0.0464	2.507×10^{-3}
	Coefficient, a_2	0.030			
Midilli	Coefficient, a	0.997	0.9998	0.0040	0.223×10^{-4}
	Coefficient, b	0.006			
	Drying coefficient, k	0.425			
	Exponent, n	0.713			
Diffusion approach	Coefficient, a	0.295	0.9988	0.0110	1.550×10^{-3}
	Coefficient, b	0.108			
	Drying coefficient, k	1.631			

correlation coefficient; standard deviation (e_s) and mean squared deviation (χ^2) were used to determine suitability of the fit. These parameters are defined as follows (Chapra & Canale, 1989):

$$r = \frac{N\sum_{i=1}^{N}\mathrm{MR}_{\mathrm{pre},i}\mathrm{MR}_{\mathrm{exp},i} - \sum_{i=1}^{N}\mathrm{MR}_{\mathrm{pre},i}\sum_{i=1}^{N}\mathrm{MR}_{\mathrm{exp},i}}{\sqrt{N\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{pre},i})^2 - \left(\sum_{i=1}^{N}\mathrm{MR}_{\mathrm{pre},i}\right)^2}\sqrt{N\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{exp},i})^2 - \left(\sum_{i=1}^{N}\mathrm{MR}_{\mathrm{exp},i}\right)^2}} \tag{2}$$

$$e_s = \sqrt{\frac{\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{exp},i}\right)^2}{N}} \tag{3}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{exp},i}\right)^2}{N - N_c} \tag{4}$$

where $\mathrm{MR}_{\mathrm{pre},i}$ is the ith predicted moisture ratio, $\mathrm{MR}_{\mathrm{exp},i}$ is the ith experimental moisture ratio, N is the number of observations and N_c is the number of constants in drying model.

3. Materials and methods

A dryer was used to conduct the drying experiment consisting of a power supply system, centrifugal fan, an electrical heater, an air supply channel, a drying chamber, four drying sieves and instrumentation for measuring air temperature, velocity and volumetric flow rate (Fig. 1). The experiments were conducted with rocco-type rough rice in an ambient air temperature of 25 °C and a relative humidity of 50%. Initial moisture ratios for rough rice used in the experiments were given in Table 2. The drying air heated electrically was driven by a fan into the drying chamber through a horizontal channel. The temperature of drying air was adjusted to the desired value with a control unit of ±0.1 °C accuracy. The average air velocity was determined by an orifice placed in the channel and adjusted with a sliding gate mounted on the inlet of the fan. The progress of the drying process was followed by weighting the sieves containing rough rice grains at regular intervals of time on a digital scale of accuracy ±0.001 g. The experiments were carried out using air at 40 °C temperature and 1.5 ms^{-1} velocity.

4. Results and discussion

Curve fitting computations with the drying rate were carried on the ten drying models relating the drying time and moisture ratio for the experimental condition with drying temperature of 40 °C and drying air velocity of 1.5 ms^{-1} and three different tempering time ($\tau = 0$ h, 0.5 h, 1 h). The results of statistical analyses on them were given in Tables 3–5. The acceptability of the drying model was based on a value for the correlation coefficient which

Table 4
Statistical analysis of the models for the tempering time $\tau = 0.5$

Model	Parameter	Value	Correlation coeff. (r)	Standart error (e_s)	Mean square of deviation (χ^2)
Newton	Drying coefficient, k	0.379	0.9900	0.0539	3.151×10^{-3}
Page	Drying coefficient, k	0.510	0.9992	0.0102	1.230×10^{-4}
	Exponent, n	0.708			
Henderson and Pabis	Drying coefficient, k	0.340	0.9863	0.0425	2.137×10^{-3}
	Coefficient, a	0.917			
Logarithmic	Drying coefficient, k	0.601	0.9988	0.0123	1.960×10^{-4}
	Coefficient, a_0	0.178			
	Coefficient, a	0.797			
Logistic	Drying coefficient, k	0.100	0.9995	0.0085	0.940×10^{-4}
	Coefficient, a_0	−0.201			
	Coefficient, a	−1.204			
Two-term exponential	Coefficient, a_1	0.519	0.9996	0.0069	0.679×10^{-4}
	Drying coefficient, k_1	1.181			
	Coefficient, a_2	0.470			
	Drying coefficient, k_2	1.039			
Geometric	Coefficient, a	0.431	0.8193	0.1434	2.431×10^{-2}
	Exponent, n	0.133			
Wang and Singh	Coefficient, a_1	−0.354	0.9888	0.0478	2.705×10^{-3}
	Coefficient, a_2	0.039			
Midilli	Coefficient, a	0.993	0.9996	0.0068	0.667×10^{-4}
	Coefficient, b	0.020			
	Drying coefficient, k	0.528			
	Exponent, n	0.865			
Diffusion approach	Coefficient, a	0.432	0.9996	0.0075	0.740×10^{-3}
	Coefficient, b	0.166			
	Drying coefficient, k	1.197			

Table 5
Statistical analysis of the models for the tempering time $\tau = 1.0$.

Model	Parameter	Value	Correlation coeff. (r)	Standart error (e_s)	Mean square of deviation (χ^2)
Newton	Drying coefficient, k	0.458	0.9944	0.0387	1.686×10^{-3}
Page	Drying coefficient, k	0.540	0.9998	0.0051	0.340×10^{-4}
	Exponent, n	0.769			
Henderson and Pabis	Drying coefficient, k	0.426	0.9929	0.0308	1.217×10^{-3}
	Coefficient, a	0.948			
Logarithmic	Drying coefficient, k	0.690	0.9991	0.0105	1.670×10^{-4}
	Coefficient, a_0	0.183			
	Coefficient, a	0.800			
Logistic	Drying coefficient, k	0.204	0.9993	0.0094	1.340×10^{-4}
	Coefficient, a_0	−0.500			
	Coefficient, a	−1.508			
Two-term exponential	Coefficient, a_1	0.520	0.9996	0.0072	0.940×10^{-4}
	Drying coefficient, k_1	0.221			
	Coefficient, a_2	0.470			
	Drying coefficient, k_2	1.069			
Geometric	Coefficient, a	0.468	0.8280	0.1418	2.585×10^{-2}
	Exponent, n	0.119			
Wang and Singh	Coefficient, a_1	−0.447	0.9950	0.0312	1.250×10^{-3}
	Coefficient, a_2	0.067			
Midilli	Coefficient, a	0.999	1.0000	0.0020	0.692×10^{-4}
	Coefficient, b	0.012			
	Drying coefficient, k	0.562			
	Exponent, n	0.824			
Diffusion approach	Coefficient, a	0.285	0.9997	0.0062	0.570×10^{-3}
	Coefficient, b	0.174			
	Drying coefficient, k	1.756			

should be close to 1, and low values for the standard error e_s and mean squared deviation χ^2. Tables 3–5 show that the most appropriate model in describing intermittent drying of thin layer rough rice is the Midilli model with a minimum r of 0.9996, and with a maximum e_s of 0.0068 and maximum χ^2 of 0.667×10^{-4} for $\tau = 0.5$ h. Besides the Midilli model, Page, diffusion approach, two-term exponential and logistic models are other adequate models in describing the experimental data. Among the models considered here, the geometric model appears to be the worst fit. The maximum deviation between theoretical results and experimental data occurs at the last hour of drying for the Midilli model.

Further regressions were undertaken to account for the effect of the tempering time on the constant and coefficient of the Midilli model. Based on the regression analysis, the accepted model coefficients and exponent were as follows:

$$\mathrm{MR} = a\exp(-kt^n) + bt \tag{5}$$

where the coefficients a, b and k are given by

$$a = 0.02\tau^2 - 0.018\tau + 0.997 \tag{6}$$

$$b = -0.044\tau^2 + 0.05\tau + 0.006 \tag{7}$$

$$k = -0.138\tau^2 + 0.275\tau + 0.425 \tag{8}$$

and the exponent n is given as

$$n = -0.386\tau^2 + 0.497\tau + 0.713 \tag{9}$$

These expressions can be used to predict the moisture content of rough rice at any time within the range of given

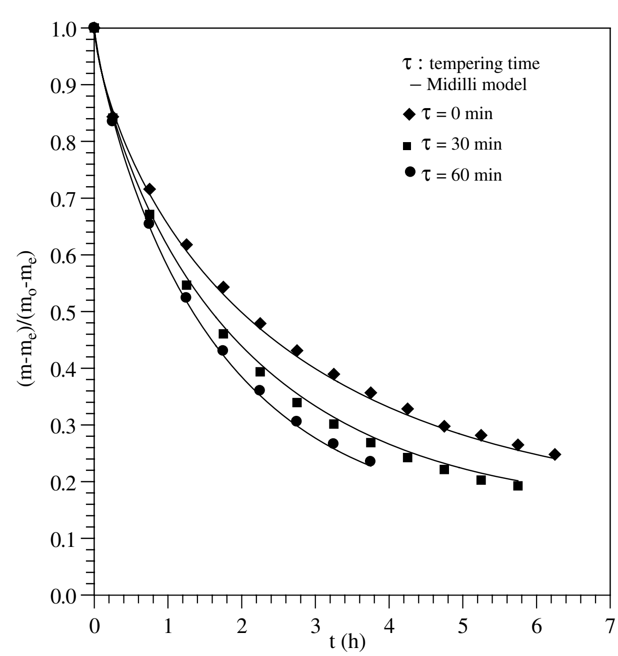

Fig. 2. Drying curves based on the Midilli model.

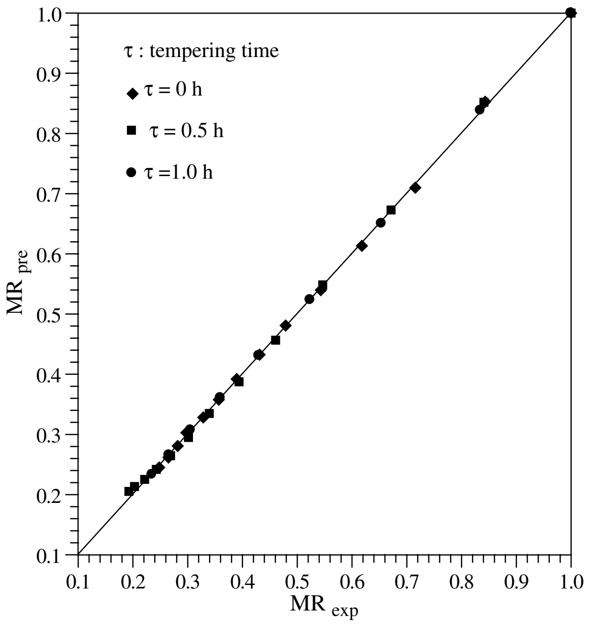

Fig. 3. Experimental and predicted moisture ratio values for rough rice.

operating drying parameters with the great accuracy. The thin-layer drying curves based on the Midilli model are presented along with the experimental data in Fig. 2. The drying rate is significantly reduced with longer tempering time. Drying process produces moisture gradients within the grain and hence drying rate slows down. Tempering period allows moisture to diffuse the external surface. Therefore, the moisture gradients within the grain decreases and the drying rate after such a tempering period increases considerable amount. With the further increase in tempering period, the increase in drying rate decreases since the decrease in moisture gradient slows down. The intermittent drying curves in which the tempering time τ was excluded may be interpreted as equivalent to the continuous drying curves with different drying constant and coefficients.

Validation of the Midilli model was confirmed by comparing the predicted moisture contents to the observed values from all the tests. The performance of the Midilli model for different drying conditions is shown in Fig. 3. The predicted data is banded around the straight line which showed the suitability of the Midilli model in describing the intermittent drying behavior of the thin layer rough rice.

5. Conclusions

Ten thin layer drying models have been analyzed for their suitability for the intermittent drying of thin layer rough rice. The results show that the Midilli model is the best fit as it produces the highest correlation coefficient and lowest standard error and mean squared deviation. The Page, diffusion approach, two-term exponential and logistic methods are other acceptable drying models in describing the experimental data. The coefficients a and b, drying coefficient k and exponent n in the Midilli model can be expressed as a polynomial function of tempering time.

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