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Mathematical modelling of drying of thin layer rough rice

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ABSTRACT

In this study, suitability of several drying models available in literature in defining thin layer drying behaviour of long-grain rough rice has been examined by using statistical analysis. For this purpose, drying models have been fitted to experimental data by means of the coefficients in the models for the drying air temperatures 40 °C, 45 °C, 50 °C, 55 °C, and 60 °C and at an airflow rate of 1.5 $\mathrm{m\,s^{-1}}$ and 3.0 $\mathrm{m\,s^{-1}}$. The results show that the Midilli et al. is the most appropriate model for drying behaviour of thin layer rough rice. Furthermore, among the two parameter models, the Page models and, among the three parameter models, the Verma et al. and the diffusion approach models give better fit. The coefficients *a* and *b*, the drying coefficient *k* and the exponent *n* in the Midilli et al. model can be expressed as a function of temperature and velocity of the drying air.

1. Introduction

Rough rice (*Oryza sativa* L.) is one of the most consumed crops as it provides staple food for more than half of the world population. Moisture content is one of the most important factors influencing the quality of rough rice during storage and it remains at high level during the harvest 24% (d. b.) and must be reduced with an appropriate drying process.

The drying characteristics of rough rice have been examined by many researchers and various models for the prediction of drying rate have been performed with more or less success. Mathematical modelling of drying is crucial for the optimization of operating parameters and performance improvements of the drying systems. In order to simulate drying, some researchers have used a liquid diffusion model, based on the assumption that the moisture transfer from the rough rice is in the liquid phase (Cihan and Ece, 2001; Kahveci et al., 2003; Hacıhafızoğlu et al., 2008; Cihan et al., 2007, 2008). However, this modelling type is complex and not suitable for practical aims. Most researchers have performed empirical or semi-empirical models for simulation of drying, given in Table 1. The primary advantage of empirical or semi-empirical models in drying simulations is their easiness to apply. Most of the models in Table 1 are derived by simplifying the general solutions of the Fick's second law or the modification of the simplified models. Therefore, most of them are not arbitrarily chosen models; on the contrary, they are based on the physiological bases. Henderson and Perry (1976) fitted their experimental data to the Newton model to simulate the thin layer drying of rough rice. Agrawal and Singh (1977) used the logarithmic model to simulate the thin layer drying of short-grain rough rice. Wang and Singh (1978) proposed a new quadratic equation to fit the single-layer drying data for medium-grain rough rice. Noomhorm and Verma (1986) presented a two term exponential model for low and high temperature drying of rough rice. Basunia and Abe (2001, 2005) found that the Page model yields an acceptable fit for the moisture content for their drying data of medium-grain rough rice. Chen and Tsao (1994) used several models to define their experimental data for the thin layer rough rice and concluded that the two term model gives the best fit among them. Das et al. (2004) showed that the Page model describes the experimental data adequately for drying of high moisture rough rice. Four different thin layer drying models were used by Chen and Wu (2001) to simulate thin layer drying of rough rice with high moisture content and the two term model was found as the

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Nomenclature

a	drying constant
b	drying constant
e_s	standard error
k	drying coefficient (h^{-1})
m	moisture content on the dry basis
mr	dimensionless moisture ratio
n	exponent
n_o	number of observations
n_p	number of parameters in the drying model
r	correlation coefficient
t	time (h)
T	temperature (°C)
V	velocity (ms^{-1})

Greek letters

φ	relative humidity
χ^2	mean squared deviation

Subscripts

e	equilibrium condition
exp	experimental
o	initial condition
pre	predicted

best fit in this study. Cihan et al. (2007, 2008) found that the most accurate model is the Midilli et al. model in defining the intermittent drying process of rough rice.

The aim of this study is to investigate the suitability of several empirical and semi-empirical models available in the literature in defining the thin layer drying behaviour of long-grain rough rice. Therefore, a model would be developed for the approximate single-layer drying behaviour for the tray and belt driers utilized in the industry.

2. Mathematical formulation

Twelve models given in Table 1 have been taken into account in this study. The moisture ratio in these model equations is defined as follows:

$$\mathrm{mr} = \frac{m - m_e}{m_o - m_e} \tag{1}$$

where m, m_o and m_e are instantaneous, initial and equilibrium moisture contents, respectively.

The coefficient of correlation (r) is one of the primary criteria for selecting the best fit. In addition to the correlation coefficient, standard deviation (e_s) and mean squared deviation (χ^2) are used to determine the suitability of the fit. These parameters are defined as follows (Chapra and Canale, 1989):

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

$$e_s = \sqrt{\frac{\sum_{i=1}^{n_o} (\mathrm{mr}_{\mathrm{pre},i} - \mathrm{mr}_{\mathrm{exp},i})^2}{n_o}} \tag{3}$$

$$\chi^2 = \frac{\sum_{i=1}^{n_o} (\mathrm{mr}_{\mathrm{pre},i} - \mathrm{mr}_{\mathrm{exp},i})^2}{n_o - n_p} \tag{4}$$

where $\mathrm{mr}_{\mathrm{pre},i}$ is the ith predicted moisture ratio, $\mathrm{mr}_{\mathrm{exp},i}$ the ith experimental moisture ratio, n_o the number of observations and n_p is the number of parameters in the drying model.

3. Materials and methods

Long-grain rough rice was used in experimental study. The rough rice was obtained from Thrace Agricultural Research Institute and not pre-treated prior to experimental study. The experimental setup for the drying experiments consists of a power supply system, centrifugal fan, an electrical heater, an air supply channel, an air collector, four drying sieves and instrumentation for measuring air temperature, velocity and volumetric flow rate. A schematic view of the experimental setup and apparatus is presented in Fig. 1. The electrically heated drying air has been driven by a 2 kW fan of 500 $m^3 h^{-1}$ flow rate trough the horizontal channel into the air collector. The air has been heated using three 1 kW and three 1.5 kW Cr–Ni electrical heaters placed with equal spacing around the heating section at the outlet of the fan. One of the 1 kW heaters has been connected to a thermostat of accuracy ±0.1 °C to monitor the air temperature automatically and the rest had manual switches, which are mounted on the control panel. Steel pipes with 200 mm length and 6 mm diameter have been placed inside the air channel after the heater to attain a uniform flow across the channel. The air flow rate has been determined by measuring the pressure drop using a differen-

Table 1 – Thin-layer drying models

Name	Model equation	References
Newton	$\mathrm{mr} = \exp(-kt)$	O'Callaghan et al. (1971)
Page	$\mathrm{mr} = \exp(-kt^n)$	Agrawal and Singh (1977)
Modified Page	$\mathrm{mr} = \exp(-(kt)^n)$	Diamante and Munro (1993)
Henderson & Pabis	$\mathrm{mr} = a\exp(-kt)$	Chhinman (1984)
Geometric	$\mathrm{mr} = at^{-n}$	Chandra and Singh (1995)
Wang & Singh	$\mathrm{mr} = 1 + at + bt^2$	Wang and Singh (1978)
Two term exponential	$\mathrm{mr} = a\exp(-kt) + (1-a)\exp(-kat)$	Sharaf-Elden et al. (1980)
Logarithmic	$\mathrm{mr} = a_0 + a\exp(-kt)$	Chandra and Singh (1995)
Diffusion approach	$\mathrm{mr} = a\exp(-kt) + (1-a)\exp(-kbt)$	Kassem (1998)
Verma et al.	$\mathrm{mr} = a\exp(-kt) + (1-a)\exp(-gt)$	Verma et al. (1985)
Two term	$\mathrm{mr} = a_1\exp(-k_1 t) + a_2\exp(-k_2 t)$	Henderson (1974)
Midilli et al.	$\mathrm{mr} = a\exp(-kt^n) + bt$	Midilli et al. (2002)