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Research Paper

Mathematical modelling of thin-layer drying according to particle size distribution in crushed feed rice

Fumina Tanaka [a], *Fumihiko Tanaka* [b,*], *Ai Tanaka* [c], *Toshitaka Uchino* [b]

[a] *JA ZENNOH FUKUREN, 4-5-23, Tenjin, Chuo-ku, Fukuoka, 810-0001, Japan*
[b] *Department of Bioproduction Environmental Sciences, Faculty of Agriculture, Kyushu University, 6-10-1, Hakozaki, Higashi-ku, Fukuoka, 812-8581, Japan*
[c] *Graduate School of Bioresource and Bioenviromental Sciences, Kyushu University, 6-10-1, Hakozaki, Higashi-ku, Fukuoka, 812-8581, Japan*

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A thin-layer drying model taking into account the particle size distribution of crushed feed rice was developed to simulate moisture content during high-temperature drying. The model was based on the Page equation, which was regarded as a suitable empirical equation to describe the thin-layer drying of rice. The proposed model, with an assumed a Rosin–Rammler distribution, successfully predicted the mean moisture content of rice during drying experiments with a mean error of 0.5% dry basis at 60, 70, and 80 °C. In order to investigate the effect of particle size distribution of rice on the drying process, a stochastic model based on Monte Carlo simulations was developed. The model developed here could provide useful information on the drying behaviour of rice particles, individually and collectively, in a thin layer bed. It was clear that uniform drying could be achieved by increasing the drying temperature.

1. Introduction

In Japan, because the price of imported crops for animal feed has risen, rice has recently received considerable attention as a substitute for maize in feed for pigs, cattle, and chickens. This has imposed a serious burden on Japanese farmers. Because the Japanese government has promoted the production of feed rice, the annual production of rice for animal feed has increased every year and reached 183,000 tonnes in 2011 (Ministry of Agriculture, Forestry and Fisheries, 2014). However, there are still numerous economic and technical issues for the use of feed rice with regard to higher production levels and high processing costs compared with imported commodities. Because of the importance of rice for human consumption, and the drying of rice is an important part of the food production chain, many researchers have investigated its drying characteristics and have developed drying models (Basunia & Abe, 2001; Cihan, Kahveci, & Hacıhafızoğlu, 2007; Hacıhafızoğlu, Cihan, & Kahveci, 2008; Tanaka et al., 2000). In order to reduce cracking or fissuring in the grains, which lead

* *Corresponding author*. Tel./fax: +81 92 642 2935.
E-mail address: fumit@bpes.kyushu-u.ac.jp (F. Tanaka).
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Nomenclature

a, c	Coefficient
b	Constant
D_p	Particle size, m
f_{Dp}	Frequency distribution of particle size
k	Drying constant defined by Eq. (1), h^{-N}
M	Moisture content, % dry basis
N, n	Exponent
$R(D_p)$	Mass cumulative probability, decimal
r	Correlation coefficient
T	Temperature, °C
t	Time, h
σ	Standard deviation
ξ	Normal random number
0	Subscript for initial condition
e	Subscript for equilibrium
MC	Abbreviation for moisture content
EMC	Abbreviation for equilibrium moisture content

to loss of quality, rice is normally dried at around 40 °C; however, feed rice can be dried at high temperatures because physical damage (cracking) poses little problem since rice grains are fed to animals as a crushed product. Also, the intramolecular change of amino acid that degrades the grain does not occur until about 90 °C (Seto, 1960). In addition, the drying rate of rice grains is accelerated by crushing them before drying: the drying rate of crushed rice was found to be significantly higher than for rough and brown rice (Tanaka et al., 2014). Tanaka et al. (2014) conducted thin-layer drying experiments with crushed rice (particle size 1190–2000 μm) with a desired moisture content (MC) of 11.1% dry basis (d.b.) for animal feed and they found that the Page model was the most suitable for describing the drying process. In practical applications, the particle size distribution of crushed feed rice becomes an important factor that affects the drying process. The batch behaviour of rice particles with widely varying sizes during drying strongly depends on the particle size distribution in a batch. Bakker-Arkema and Liu (1997), Liu, Montross, and Bakker-Arkema (1997) and Liu and Bakker-Arkema (1997) proposed a stochastic drying model including one random parameter, initial MC, for drying maize. Cronin and Kearney (1998) developed a stochastic drying model for a vegetable tray dryer with two random parameters; the initial MC and the drying rate. For the pneumatic conveying drying of rice powder, Tanaka, Maeda, Uchino, Hamanaka, and Atungulu (2008) proposed a Monte Carlo model with two random parameters generated with an assumption of multivariate normal distribution by means of a covariance decomposition algorithm. The model could describe the complex behaviour of rice particles in a batch during pneumatic conveying drying. Tanaka, Morita, et al. (2008) also investigated the batch drying behaviour of raw rough rice using a Monte Carlo model based on statistically quantified random parameters. Generally, deterministic models have been found to be useful to predict and control the mean moisture content of a batch; however, they can provide only limited information for evaluating quality during agricultural products drying. In order to describe batch behaviour with some kinds of response variables, a drying model with random variables becomes a powerful tool for predicting the drying process of a batch. In this study, we focused on crushed brown rice for animal feeding dried in high temperature conditions, and we developed a drying model to investigate the effect of rice particle size on drying behaviour.

The objectives of this study were to: (1) develop a thin-layer drying model taking into account the particle size distribution of crushed feed rice at high temperatures, (2) investigate the effect of particle size distribution by assuming Rosin–Rammler and normal distributions for drying curves at 60, 70, and 80 °C. The findings of this study can help understand and improve the thin-layer drying of crushed feed rice. Because the samples used in our earlier work (Tanaka et al., 2014) were graded using a standard sieve with screen openings of 1190, 1400, 1700, and 2000 μm, and the drying characteristics of the rice were determined for each grade, the effect of particle size distribution on the drying characteristics are not discussed.

2. Experimental procedures

2.1. Materials

Freshly harvested japonica rice grains (*Oryza sativa* L., japonica, ‘Mizuhochikara’) were obtained from a local farm in Fukuoka, Japan. The rough rice was cleaned by removing any debris such as stalks and empty husks. After cleaning, the rough rice samples were husked to remove the hulls (FC2K; Otake Co., Ltd., Aichi, Japan). Whole grain brown rice was obtained using a rice quality inspector (RGQI120AS; Satake Co., Ltd., Hiroshima, Japan). The samples of brown rice were crushed using a mill mixer (IFM700G; Iwatani Co., Ltd., Tokyo, Japan).

In order to determine the particle size distribution of crushed feed rice, the samples were graded using a standard sieve with screen sizes of 250, 500, 710, 1000, 1190, 1400, 1700, and 2000 μm. The distribution was approximated by using the Rosin–Rammler distribution in accordance with Tanaka et al. (2014).

2.2. Methods

Figure 1 shows a schematic representation of the experimental apparatus. The system included a humidified incubator to control the temperature and humidity of air, a sample holder made of a polyvinylchloride (PVC) pipe of 83 mm internal diameter and 3 mm wall thickness with a metal screen (0.18 mm) at the bottom, and a fan for blowing air. The air flow rate toward the crushed grains was 5.5×10^{-3} m^3s^{-1} per 100 g; the air velocity was 0.26 ms^{-1}, at which rate the crushed rice samples did not float.

Thin-layer drying experiments were carried out in a humidified incubator (HPAV-48-20; Isuzu Co., Ltd., Niigata, Japan) set at 60, 70, or 80 °C and with relative humidity (RH) of 10%. Temperature and RH of the drying air were measured using a thermocouple and a humidity sensor (9701; Hioki E. E. Co.,