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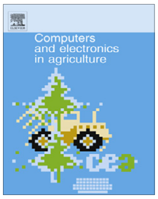

Original papers

Changes in moisture effective diffusivity and glass transition temperature of paddy during drying

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ABSTRACT

Moisture effective diffusivity and glass transition temperature (T_g) of paddy during drying were investigated by drying five varieties of paddy with an initial moisture content of 21.1–24.4% wet basis and a temperature range of 45–70 °C in a constant temperature and blast oven. With an increase in drying temperature, the desorption rate and moisture effective diffusivity of paddy kernels increased and drying duration decreased. At a drying temperature of 45 °C, the curve of the desorption rate changed slowly and drying duration was longer. Most of the five paddy varieties had similar desorption rates at drying temperatures of 45–70 °C, and their moisture effective diffusivities were in the range of 2.638×10^{-9}–$2.514 \times 10^{-8}\,\mathrm{m^2\,min^{-1}}$ with an active energy of 6.547–36.913 kJ $\mathrm{mol^{-1}}$. T_g values of long-grain variety ‘Zhunliang you’ and two medium-grain varieties ‘Zhongjia zao’ and ‘Dianjiang’ determined using the differential scanning colorimeter method increased from 38.7 °C to 51.2 °C when their moisture contents decreased from 20% to 13%. Under similar conditions, differences in T_g values of the three varieties of paddy were observed. When the moisture content of the three varieties of paddy decreases from 20% to 13% at drying temperatures of 50–70 °C, drying time should be 60–80 min for less than 10% damage to kernels.

1. Introduction

Rice is a major food crop and sustains more than half of the world’s population (USDA, 2007). It is consumed predominantly in the form of whole kernels. Rice fissuring (cracking) is of great concern to the rice industry, since fissured kernels are more susceptible to breakage during the milling process. Previous studies on rice fissuring suggest that fissure formation could occur because of either rapid moisture absorption (Kunze and Prasad, 1978; Siebenmorgen and Jindal, 1986; Banaszek and Siebenmorgen, 1990; Lan et al., 1999; Jia et al., 2002) or desorption (Kunze, 1979). During the post-harvest drying process of paddy, fissures (Kunze and Calderwood, 1985) may develop when rice is dried at a high temperature (e.g., 60 °C). A traditional hypothesis on fissure formation in a rice kernel suggests that fissures are caused by moisture gradients created during fast drying (Ban, 1971; Sarker and Kunze, 1996; Jia et al., 2002). To reduce these moisture gradients, rice is usually held between passes in a multi-pass drying process. This practice is known as tempering, which refers to an equilibration of moisture content (MC) inside a kernel and serves to equalize the moisture content throughout the mass (Steffe and Singh, 1980). Tempering temperatures ranging from 35 °C to 60 °C have been used (Cnossen et al., 1998; Li et al., 1999). Higher tempering temperatures have proven to be effective in preserving head rice yield (HRY) and reducing tempering durations. Batcher et al. (1958) reported that drying at elevated temperatures (up to 71 °C) caused neither marked improvement nor deterioration in the cooking quality of milled rice; however, Bonazzi et al. (1997) considered that tempering temperatures higher than 60 °C are seldom used, probably because 60 °C is a high temperature used for rice drying, and a higher drying temperature would cause a dramatic decrease in head rice yield (HRY). Cnossen and Siebenmorgen (2000) suggested that tempering above the glass transition temperature (T_g) of rice kernels would be more effective in preserving HRY. At a MC and temperature below the glass transition temperature (T_g), starch exists as a “glassy” material, with low expansion coefficients, specific volume, and diffusivity.

Abbreviations: D_{eff}, effective diffusivity; D_0, pre-exponential factor of the Arrhenius equation; DSC, differential scanning colorimeter; E_a, activation energy; EMC, equilibrium moisture content; T_g, glass transition temperature; HRY, head rice yield; IMC, initial moisture content; MC, moisture content; w.b., wet basis.

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As the kernel temperature passes through T_g, the starch goes from a 'glassy' into a 'rubbery' state. Above the T_g, starch exists as a rubbery material with higher expansion coefficients, specific volume, and diffusivity (White and Cakebread, 1966; Slade and Levine, 1995). Laboratory and pilot-scale experiments have suggested that glass transition behavior can be used to explain rice fissure formation (Cnossen and Siebenmorgen, 2000; Cnossen et al., 2002; Yang and Jia, 2004). However, there are few reports on T_g of Chinese paddy varieties.

Desorption of moisture from grain kernels during drying nearly always occurs in the falling-rate drying period in which there is no free moisture. The theory of falling-rate desorption has been thoroughly developed (e.g., Henry, 1939; Luikov, 1966). The resulting two coupled partial differential equations that describe heat and moisture diffusion may generally be uncoupled because of the different rate of heat transfer as compared to mass transfer during drying (Parti, 1993), leading to thin-layer drying equations referred to herein as diffusion equations. Many empirical equations developed often have as good as or greater accuracy in a specific application with less computational effort than theoretical equations. The exponential drying equation (Lewis, 1921; Sherwood, 1936) is useful in some cases for describing thin-layer drying, but it gives a poor description of the initial part of the drying process (Hukill and Schmidt, 1960); maybe it is more accurate for grain storage because there is more boundary layer resistance than with drying due to slow-moving or even stagnant air in storage situations. Page (1949) developed an empirical equation that has proven to be considerably more accurate than the exponential drying equation. The Page equation is often accepted as the preferred equation for drying (ASAE Standards, 1994). Diffusion equations have usually been based on the simple assumption that grain kernels are homogeneous. Thus, we wanted to develop a modified Page equation to describe desorption rates of Chinese paddy varieties during drying.

With progress in grain harvest by agricultural machines in China, harvested paddy contains more foreign materials, and a highly efficient drying process is needed for newly harvested paddy. This study was performed to determine the desorption rates of five Chinese paddy varieties dried in a blast thermostatic oven with our developed diffusion equation and analyze effective diffusivity and glass transition temperature for a thorough analysis of the drying phenomenon for rough rice and improving the efficiency of drying systems.

2. Material and methods

2.1. Sample preparation

In this study, we used three varieties of japonica species ('Longyang', 'Xiangdao', and 'Yanfeng') and three varieties of indica species ('Zhongjia zao', 'Zhunliang you', and 'Dianjiang') (Table 1). Samples were prepared on an approximately 25% wet basis by adding distilled water, equilibrating for two weeks in a temperature-controlled cabinet (10 °C), and shaking once a day.

2.2. Sampling during drying of paddy and analysis of desorption rates

High-moisture samples were placed in a round-bottom aluminum sieve (22 cm in diameter and 5 cm in depth) with a 2-mm pore size and dried in an electric blast thermostatic oven (DHG-9040A; Hangzhou Lantain Instrument Co. Ltd., China). The oven gives accurate and reliable temperature via a digital display microcomputer controller with the temperature control protect and timing function. The hot air circulating system consists of a fan consecutive operating under high temperature and suitable air channel. The work room has uniform temperature ranging from room temperature (RT) plus 10 °C to the highest value of 250 °C; Temperature resolution 0.1 °C; the fluctuations of constant temperature is ±1 °C.

About 500 g of the sample of each variety was dried at each temperature of 45 °C, 50 °C, 55 °C, 60 °C, 65 °C, and 70 °C. At each temperature, an aliquot of 15 g was sampled at sampling intervals 0, 10, 20, 40, 60, 80, 100, 120, 150, and 180 min for drying at 55 °C, 60 °C, 65 °C, and 70 °C, and delayed to 210 min for 45 °C and 50 °C drying. After drying, each sample was maintained at room temperature for 4 h and then stored at 4 °C. Of 15 g, 10 g was used to determine moisture content by using the oven method, and 5 g was used to determine the length and width of paddy kernels by using a rice appearance quality detection instrument (JMWT12; Satake, Japan).

Diffusion equations have usually been based on the simple assumption that grain kernels are homogenous. When diffusion in a paddy kernel takes place at a constant temperature, the moisture diffusion equation alone is sufficient for describing moisture movement.

Page (1949) altered the exponential equation (Eq. (1)) by adding an exponent to the time variable to improve the fit of his corn-drying data, which yielded Eq. (2):

$$\mathrm{MR} = \exp(-kt) \tag{1}$$

$$\mathrm{MR} = \exp(-kt^n) \tag{2}$$

where MR is the average moisture ratio of the material at any given time, decimal; $\mathrm{MR} = (\mathrm{M}_t - \mathrm{M}_e)/(\mathrm{M}_0 - \mathrm{M}_e)$; M_t is average moisture of the material at any given time (t), decimal wet basis; M_e is equilibrium moisture content (decimal wet basis); M_0 is initial moisture content (decimal wet basis); t is time from the beginning of the drying process (min); and k and n are product-specific constants. We have provided the modified form of Page's equation:

$$\mathrm{MR} = a\ \exp[-kt^n \cdot \exp(-b/(\theta + 273))] \tag{3}$$

where θ is temperature (°C) and a, b, k, and n are equation constants.

From Eq. (3),

$$\begin{aligned} \mathrm{d}(\mathrm{M}_t)/\mathrm{d}t = {} & (\mathrm{M}_0 - \mathrm{M}_e) \cdot a \cdot \exp(-kt^n \exp(-b/(\theta + 273))) \\ & \cdot (-knt^{n-1} \exp(-b/(\theta + 273))) \end{aligned} \tag{4}$$

where $\mathrm{d}(\mathrm{M}_t)/\mathrm{d}t$ is the moisture desorption rate of paddy kernels ($10^{-5}\ \mathrm{min}^{-1}$).

Table 1
Samples used in this study.

No.	Sample	Producing region	Type	IMC[a] (%)	Drying temp. (°C)
1	Longyang	Heilong jiang, China	Medium grain, japonica rice	23.29	45, 55, 65
2	Yanfeng	Jilin, China	Long grain, japonica rice	22.01	45, 55, 65
3	Zhunliang you 1	Hunan, China	Medium grain, indica rice	24.47	45, 55, 65
4	Zhongjia zao	Hunan, China	Long grain, indica rice	21.07	45, 55, 65
5	Zhunliang you2			24.35	50, 60, 70
6	Dianjiang	Chongqing, China	Medium grain, indica rice	22.59	50, 60, 70

[a] IMC, initial moisture content.