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Moisture diffusion modeling of parboiled paddy accelerated tempering process with extended application to multi-pass drying simulation

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Abstract

Parboiled paddy grain tempering process, often employed in multi-pass drying for milling quality improvement, is theoretically modeled considering a multi-component prolate spheroid geometry in prolate spheroidal coordinate system. The finite difference formulation analyzed the moisture diffusion during tempering and established the effect of vacuum in tempering acceleration. Experimental procedure reported already is essentially a double-pass drying (90 and 75 °C) of parboiled paddy with tempering stage at a critical moisture content (20.48% d.b.), where the moisture equilibration is accelerated by the application of vacuum (0–700 mm of Hg vacuum gauge). Boundary conditions of previously developed drying model were appropriately modified to model the tempering process. A supplemental fixed boundary condition with the regular derivative boundary condition and incorporation of tempering diffusivity factor modeled the tempering process and explained the effect of vacuum in tempering acceleration. Analysis of moisture history of nodes indicated that starch component moisture moved towards husk through bran component and the moisture profiles clearly demonstrated the effect of vacuum in temperature acceleration. An exponential relationship ($R^2 = 0.9813$) adequately modeled the variation of diffusivity factor with the applied vacuum in accelerated tempering. The developed tempering model with drying model can simulate any multi-pass drying processes as well as help perform sensitivity analysis on factors, design equipment, and optimize operations.

Keywords: Paddy; Tempering; Mathematical model; Prolate spheroid; Diffusion; Drying; Vacuum

1. Introduction

Paddy parboiling is a hydrothermal pretreatment undertaken to improve the paddy milling characteristics. The operation, however, increases grain moisture and consequently a greater extent of drying is required prior to milling resulting in greater energy expenditure. In addition, the need of increased moisture removal makes the parboiled paddy drying operation more delicate. Unlike raw paddy that has moisture in the ⩽30% dry basis (d.b.) range, parboiled paddy may reach 60% d.b. moisture after the steaming process (Bakshi and Singh, 1979). As for milling quality of parboiled paddy is concerned, the drying method is central in the parboiling process (Bhattacharya and Indudhara Swamy, 1967). Since the rice kernel is fragile and sensitive to thermal and moisture stresses during drying, the economic advantage of parboiling cannot be fully realized if the drying is not properly accomplished. It can also be asserted that when dried meticulously, parboiled paddy achieves sufficient mechanical strength such that virtually no breakage results in subsequent milling processes.

Since a greater amount of moisture (≈55% d.b. initial to ≈12% d.b. final) has to be removed, parboiled paddy

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drying should be a batch process involving multiple-stages with intermediate tempering operations to prevent thermally induced grain physical damage (Elbert et al., 2001). Multi-pass drying is also followed in raw paddy drying to obtain better milling results. Even though head rice yield increased with the increased number of drying passes and reduced drying temperatures, these procedures resulted in increased total drying time thereby reducing the operation throughput. Bhattacharya and Indudhara Swamy (1967) reported that there exists an optimum moisture level, known as critical moisture content, at which tempering should be initiated and, after its completion, the grain can be safely dried to final moisture without any broken grain during milling. The critical moisture content values reported by several researchers, such as 10–23% d.b. (Bhattacharya and Indudhara Swamy, 1967), 25% d.b. (Ali and Ojha, 1976), 20–21% d.b. (Chakraverty, 1976), 19–25% d.b. (Mahindru, 1995), and 20.48% d.b. (Igathinathane and Chattopadhyay, 2002), clustered around 20% d.b.

Parboiled paddy tempering process is traditionally carried out in ambient conditions, and moisture diffusion occurring naturally makes it a very slow process. During tempering, moisture and thermal gradients and the associated stresses developed in the grain during initial drying become equilibrated due to the respective moisture and thermal diffusion processes (Igathinathane and Chattopadhyay, 2002). Steffe and Singh (1980b) reported that the tempering period employed is often based on the experience of the operators, and the commonly followed tempering periods in commercial drying vary widely between 4 and 24 h. However, recently, Igathinathane and Chattopadhyay (2002) established that tempering can be accelerated by application of vacuum. A maximum 78% time reduction in tempering and 72% time reduction in double-pass drying with tempering could be achieved with the application of 700 mm of Hg compared to conventional tempering at atmospheric pressure. Other researchers proposed in studies with raw paddy that application of high temperature during tempering was an efficient means of reducing fissures (Cnossen and Siebenmorgen, 2000; Iguaz et al., 2006; Aquerreta et al., 2007).

Only limited published research was available on the moisture diffusion inside the rice kernel during tempering process. Steffe and Singh (1980b) considered a multi-layered composite spherical geometry and theoretically modeled the liquid moisture diffusion in rough rice grains during tempering using Fick's law of diffusion. They used the determined liquid diffusion coefficients of the components of rough rice, such as, starch, bran, and husk from their drying study (Steffe and Singh, 1980a) to model the tempering process. Yang et al. (2002) used finite element models to simulate the single kernel drying and tempering behavior of rice in terms of moisture and temperature distributions inside rice kernels. Based on this work Jia et al. (2002) have developed a Matlab based software package with C++ compiler for describing single-kernel drying, tempering, and internal stress using finite element analysis. Empirical equations described the thermal and moisture diffusion process.

Igathinathane and Chattopadhyay (1999a,b) modeled moisture diffusion in single component, polished, parboiled rice as well as multi-component paddy grain during drying and determined the liquid diffusion coefficients of starch, bran, and husk components in the form of Arrhenius relationships using prolate spheroid geometry in prolate spheroidal coordinate system. The drying model of Igathinathane and Chattopadhyay (1999b) can be suitably modified to address the moisture diffusion in the tempering process using the moisture diffusivity of components already determined. Their modeling technique is similar to that of Steffe and Singh (1980b). Combined application of drying and tempering models can fully simulate any multi-pass or intermittent drying process numerically.

The objectives of the present research work are to (i) model the moisture diffusion in multi-component rice grain during tempering assuming prolate spheroid geometry in prolate spheroidal coordinate system; (ii) visualize the moisture profile development inside rice grain during tempering, and determine the effect of applied vacuum in tempering acceleration; and (iii) simulate a multi-pass drying comprised of a first-pass followed by tempering and a final second-pass drying.

2. Materials and methods

2.1. Test material, preparation, multi-pass drying, and accelerated tempering process

A medium grain variety of paddy 'Pankaj' served as the test material. A combination soaking procedure (Igathinathane et al., 2005) involving high (80 °C) and reduced temperature (70 °C) completed the paddy soaking to moisture saturation in about 3.5 h. A selected steaming treatment of 98.07 kPa pressure gauge for 600 s, based on preliminary trials, produced the parboiled paddy with desirable milling qualities.

The multi-pass drying implemented in the study was a double-pass drying with a tempering stage at the critical moisture content between drying passes. The critical moisture content in the double-pass drying was considered to be the intermediate moisture content at which the first-pass is stopped and the grain is tempered before the second-pass drying. This specification resulted in the least total in-dryer time. Unlike other studies where fissure reduction is the major concern, it should be noted that the critical moisture content defined in this study was based on in-dryer time reduction. A first-pass drying air temperature of 90 °C and second-pass at 75 °C as suggested by Ali and Ojha (1976) were used in a commercial laboratory scale fluidized bed dryer.

An accelerated tempering vessel developed by Igathinathane (1997) was used to conduct the accelerated tempering studies of first-pass dried grain at various levels of vacuum (100, 200, 300, 400, 500, 600, and 700 mm of Hg vacuum