Journal of Food Engineering 141 (2014) 99–106

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Modelling of brown rice and limited-water cooking modes and its potential use for texture prediction

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ARTICLE INFO

Article history:
Received 20 June 2013
Received in revised form 23 April 2014
Accepted 10 May 2014
Available online 16 May 2014

Keywords:
Cooking
Water-to-rice ratio
Brown rice
Water transport
Gelatinization
Texture

ABSTRACT

This paper describes the adaptation of a one-dimensional rice cooking model including water transfer, starch phase transitions and swelling to simulate both milled and brown *Chu-cheong* and *Chil-bo* rice cultivars cooked in excess water or in limited amounts of water. The pericarp was found to play a temperature-dependent role during steeping of brown rice. At 50 °C, surface mass-transfer resistance was identified whereas from 75 °C the pericarp ruptured. Despite pericarp rupturing, apparent water diffusion coefficients for brown rice ($\sim 1.9 \times 10^{-10}$ m^2 s^{-1}) were lower than for milled rice ($\sim 3.3 \times 10^{-10}$ m^2 s^{-1}). This was due to the mechanical constraining effect of pericarp with respect to water uptake. In the limited-water cooking mode, predicted water and gelatinization profiles of four selected cooking procedures explained the texture of cooked rice. Indeed, the highly hydrated gelatinized periphery of the cooked grain resulted in high "initial starchy coating" sensory scores whereas the uncooked core increased instrumental firmness.

1. Introduction

Along with wheat and maize rice is one of the world's major cereal crops and is the staple food for nearly half population of the world. Starch, the principal component of the rice kernels, is an excellent source of food energy. Rice can be consumed as milled rice or brown rice. Besides endosperm, brown rice includes the embryo and an additional hard outer layer called bran comprising the aleurone and pericarp. Rice bran and the embryo bud represent 8% of the brown Japanese rice (*Japonica* type) kernel (Muramatsu et al., 2006). Whole-grain cereals such as brown rice have received considerable attention in recent decades due to their unique bioactive components. Indeed, rice bran contains an array of health-promoting components such as phytosterol, gamma oryzanol, tocopherols, vitamins and various dietary fibres (Gani et al., 2012).

Rice is generally cooked using either excess or limited amounts of water. The excess-water method consists of boiling rice in large quantities of water followed by draining. The limited-water method consists of cooking rice – usually in a rice cooker – with a given water-to-rice ratio ranging from 1:1 to 4:1 (w/w) until all the water is absorbed. The temperatures range from 20 °C to 120 °C, depending on whether pressure is used and whether the method includes pre-cooking or pre-soaking steps.

The choice of an appropriate set of cooking parameters is essential to obtain a specific texture of cooked rice. Han and Lim (2009) reported that changing the soaking temperature from 25 °C to 50 °C before cooking increased the water content and the adhesiveness of cooked brown rice and decreased instrumentally measured hardness. Similarly, using several rice cultivars, Billiris et al. (2012) and Bett-Garber et al. (2007) observed that increasing the water-to-milled rice ratio from 1:1 to 2.5:1 (w/w) increased sensory stickiness while decreasing instrumental and sensory hardness.

The two coupled phenomena underlying the difference in texture are water uptake and starch gelatinization. Evaluating water distribution within a starchy matrix by MRI both during and after cooking provides useful information for monitoring texture (Kojima et al., 2001; Maeda et al., 2009; McCarthy et al., 2002; Sekiyama et al., 2012). For instance, Irie et al. (2004) were able to obtain specific MRI moisture "signatures" for spaghetti subjected to different thermal treatments before cooking. Samples with a markedly low moisture region in the native core were harder than samples with more even water distribution.

As observed by MRI (Horigane et al., 2006), the outer pericarp of brown rice is resistant to water transfer during cooking, resulting in lower water absorption than for milled rice in the same cooking conditions (Billiris et al., 2012; Muramatsu et al., 2006). Several models describing brown rice water uptake in excess water for steeping temperatures ranging from 5 °C to 65 °C are cited in the

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http://dx.doi.org/10.1016/j.jfoodeng.2014.05.008
0260-8774/

literature but most are either empirical (Cheevitsopon and Noomhorm, 2011; Shittu et al., 2012; Thakur and Gupta, 2006) and/or do not explain the role of pericarp in the water uptake properties of brown rice (Bello et al., 2010; Muramatsu et al., 2006). Some authors studied the barrier effect of the pericarp by introducing a limiting surface mass-transfer resistance (Engels et al., 1986; Frias et al., 2002; Meyer et al., 2007), but only in experiments performed at low temperatures (less than 60 °C). Engels et al. (1986) and Igathinathane and Chattopadhyay (1999) added an external layer compartment. In the first case, the experiments were performed at 30 °C and 50 °C and in the second case during drying, i.e. with much less variation in moisture content (from 55% to 4% db) than during cooking (from 12% to 400% db). It should be noted that none of the studies considered the gelatinization phenomenon and the swelling of the kernel due to water uptake.

The model developed by Briffaz et al. (2014) describes simultaneous water transport, starch gelatinization and swelling during cooking of a single milled rice grain in excess water at constant temperatures. The first aim of the present study work was to adapt the model to brown rice in order to model water uptake kinetics during steeping in excess water. The second aim was to adapt this model to predict water uptake, gelatinization and swelling in the limited-water cooking mode and to compare the results with those of the texture of cooked rice.

2. Mathematical formulation

2.1. Basic principles

In the model of Briffaz et al. (2014), the grain is assumed to be composed of two liquid water populations (in native starch and excess water since starch starts to gelatinize) moving through an anhydrous starch network (solid phase) which swells due to water uptake. Once starch starts to gelatinize, i.e. when water content reaches a critical value X_1^{cr} (which depends on temperature), it can take up excess water X_{1g} (kg kg^{-1} db). In the case of brown rice, boundary conditions as well as apparent water diffusivities will be adapted. In the limited-water cooking mode, and for a given water-to-rice ratio, the rice grain absorbs a finite volume of cooking water medium. After full absorption, the water flux becomes zero at the rice grain interface and a holding period begins during which water is redistributed within the rice grain.

2.2. Major assumptions of the models

The assumptions underlying the model are the same as those mentioned by Briffaz et al. (2014). Basically, we consider a single spherical rice grain without an internal temperature gradient and being composed of two water populations: water absorbed by starch in native state ($i = 1n$) and excess water absorbed by starch after it starts to gelatinize ($i = 1g$) and anhydrous starch ($i = 2$) (all dry solid is assumed to be starch). Water transports equations are expressed by Fick's law.

2.3. Mass conservation

The mass balance equations for the two water populations expressed in Lagrangian coordinates were developed by Briffaz et al. (2014):

$$\left.\begin{aligned}\left(\frac{\partial X_{1n}}{\partial t}\right)_{\xi,t} &= \frac{1}{\xi^2}\frac{\partial}{\partial \xi}\left(\xi^2\left(\frac{r^2\rho_2}{\xi^2\rho_2^0}\right)^2 D_{1n}\frac{\partial X_{1n}}{\partial \xi}\right)\\ \left(\frac{\partial X_{1g}}{\partial t}\right)_{\xi,t} &= \frac{1}{\xi^2}\frac{\partial}{\partial \xi}\left(\xi^2\left(\frac{r^2\rho_2}{\xi^2\rho_2^0}\right)^2 D_{1g}\frac{\partial X_{1g}}{\partial \xi}\right) \quad X_{1n} \geqslant X_1^{cr}\end{aligned}\right\} \tag{1}$$

where r and ξ are the Eulerian and Lagrangian coordinates respectively (m), ρ_2^0 and ρ_2 are the intrinsic and apparent densities of anhydrous starch (kg m^{-3}) respectively, D_{1n} and D_{1g} are the water apparent diffusivities (m^2 s^{-1}) in native and gelatinized starch respectively, and X_1^{cr} is the critical water content required for the start of gelatinization (kg water kg^{-1} db). At any time t and any position ξ, total local water content X_1 (kg water kg^{-1} db) is given by the sum:

$$X_1 = X_{1n} + X_{1g} \tag{2}$$

Anhydrous starch mass conservation equation written between Eulerian and Lagrangian reference frames is given by:

$$\rho_2 r^2 dr = \rho_2^0 \xi^2 d\xi \tag{3}$$

By integrating Eq. (3) over the solid spherical volume as:

$$r^3 = \int_0^{\xi} \frac{3\rho_2^0}{\rho_2}\xi^2 d\xi \tag{4}$$

it is possible to obtain the Eulerian coordinates of each Lagrangian coordinate of the sphere.

2.4. Initial conditions

The water content is initially uniformly distributed inside the rice grain so that:

$$\left.\begin{aligned}X_{1n} &= X_{1n,0} \quad \text{for } t = 0 \quad \text{and} \quad 0 \leqslant \xi \leqslant \xi_{\max}\\ X_{1g} &= X_{1g,0} \quad \text{for } t = 0 \quad \text{and} \quad 0 \leqslant \xi \leqslant \xi_{\max}\end{aligned}\right\} \tag{5}$$

where $X_{1n,0}$ and $X_{1g,0}$ are the initial water content (dry basis) of the starch in the native and gelatinized state respectively.

2.5. Boundary conditions

2.5.1. At the centre of the rice grain

The fluxes of water in native and gelatinized starch at the centre of the spherical rice grain ($\xi = 0$) and for $t > 0$ are equal to zero. So the Neumann boundary conditions give:

$$\left.\begin{aligned}\left(\frac{\partial X_{1n}}{\partial \xi}\right)_{\xi=0,t} &= 0 \quad (a)\\ \left(\frac{\partial X_{1g}}{\partial \xi}\right)_{\xi=0,t} &= 0 \quad (b)\end{aligned}\right\} \tag{6}$$

2.5.2. At the brown rice–water interface in excess water at $T < T_g$

At temperatures below gelatinization (T_g), as the pericarp is unbroken, water transport at the brown rice grain surface boundary ($r_{\max}$) is assumed to be controlled by a surface mass-transfer resistance, noted $1/k_{brown}$ (s m^{-1}). As a consequence, water flux density j_i^E (kg m^{-2} s^{-1}) of water population i ($1n$ or $1g$) in Eulerian coordinates can be written as:

$$j_i^E = \frac{\rho_2(X_{i,\infty} - X_i)}{1/k_{brown}} \quad r = r_{\max} \tag{7}$$

where $X_{i,\infty}$ is the equilibrium water content at a temperature below gelatinization (kg kg^{-1} db). By performing a mass balance between the Eulerian and Lagrangian coordinate systems, it is possible to obtain the Lagrangian water flux density j_i^L (kg m^{-2} s^{-1}) for each water population i:

$$j_i^L = \left(\frac{r}{\xi}\right)^2 \frac{\rho_2(X_{i,\infty} - X_i)}{1/k_{brown}} \quad \xi = \xi_{\max} \tag{8}$$

Eq. (8) is the Neumann boundary condition in Lagrangian coordinates that applies to the brown rice grain interface at any temperature below gelatinization (e.g. 50 °C).