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Modelling of water transport with convection effects on amylose transfer in a swelling, eroding and gelatinizing starchy matrix

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ABSTRACT

A 1D mechanistic model was developed to describe water, deformation, amylose transport and starch gelatinization inside rice grains during cooking. Four migrating species were considered: two water populations according to the state of the starch, soluble amylose and an insoluble solid phase network. Three coupled mass transport PDE were formulated assuming diffusional mass transport and using a Lagrangian-Eulerian framework. The model integrates the convective effect of a water flux on the transport of soluble amylose. Rice grain deformation was the result of both water-induced swelling and erosion of the surface of the solid phase, assuming a zero-order kinetic process. The model was adjusted on a milled *Chil-bo* rice cultivar steeped in excess water at 75 °C and 95 °C. After 30 min at 95 °C, which is the standard cooking time, water uptake, leaching of soluble amylose and the amount of eroded material were 3.15 kg kg^{-1} db, 5.0% and 15.5% (w/w) respectively. Using the predicted distribution of species within the grain, the model could help to control the texture of cooked rice.

1. Introduction

Rice (*Oryza sativa* L.) is one of the mostly widely grown food crops worldwide and is an important staple food for more than half the world population. A crude rice grain is mainly composed of starch, with small amounts of proteins, lipids and water. Starch is present in rice grain in the form of granular structures and is composed of two high molecular weight polymers of anhydroglucose: amylose, a mainly linear polymer made up of 250–5000 glucose units, and amylopectin, a branched polymer of very high molecular weight made up of 10,000–100,000 glucose units (Perez and Bertoft, 2010).

Rice is cooked by boiling either with an adjusted amount of water, or in excess water. While being cooked, rice undergoes a series of dramatic physical-chemical changes. When the grain comes into contact with boiling water, it takes up water and swells due to water-induced starch gelatinization (Vandeputte et al., 2003) and releases starch and other materials into the water cooking medium (Patindol et al., 2010). Mainly amylose and amylopectin are lost into the water medium during cooking (Cameron and Wang, 2005; Hanashiro et al., 2004; Ong and Blanshard, 1995; Patindol et al., 2010). Solid losses may be linked to disruption of the cells at the surface of the grain, as observed by microscopy (Briffaz et al., 2012). In the adjusted-water method, the released material is condensed and coated onto the surface of cooked grains where it forms a starchy coated layer when the water is totally absorbed (Okuda et al., 2009; Tamura and Ogawa, 2012).

The extent of released material greatly depends on the cooking conditions and on the variety of rice. Solid and soluble losses have been found to increase as a power function of cooking duration (Yadav and Jindal, 2007) with qualitative and quantitative variations among cultivars (Cameron and Wang, 2005; Ong and Blanshard, 1995; Patindol et al., 2010). Released material dramatically affects the properties of the cooked rice including its texture. Indeed, the higher the amount of leached amylose, the harder the cooked rice (Cameron and Wang, 2005; Ong and Blanshard, 1995). In terms of instrumental cooked rice stickiness, negative correlations were obtained regarding leached amylose-amylopectin ratio and the amount of leached material in the cooking medium (Mestres et al., 2011; Patindol et al., 2010).

It is consequently of great interest to model the release of material into the water cooking medium for a better understanding and control of the mechanisms controlling the texture of cooked rice grain. Unfortunately, in the case of food cooked in water, most

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Nomenclature

Notation

D	apparent diffusivity coefficient ($m^2.s^{-1}$)
F	function defined in Eq. (20)
J_i^*	mass flux density relative to the local mass average velocity ($kg.m^{-2}.s^{-1}$)
m_i	total mass of species i (kg)
N_i	mass flux of species i in the Eulerian reference frame ($kg.m^{-2}.s^{-1}$)
r	Eulerian spherical coordinate (m)
$r_{\max}$	external sphere radius (m)
S	surface area (m^2)
t	time (s)
T	temperature (°C)
V	volume (m^3)
v_i, v	velocity ($m.s^{-1}$)
v^*	mass average velocity ($m.s^{-1}$)
A,M	matrices in Eqs. (8)–(10) and (11)
VG	volume gain ($m^3.m^{-3}$)
X_i	content on dry basis ($kg.kg^{-1}db$)

Greek symbols

∇	gradient operator
ξ	Lagrangian spherical coordinate (m)
ω_i	mass faction ($kg.kg^{-1}$)
ρ, ρ_i	density ($kg.m^{-3}$)
τ	degree of starch gelatinization

Subscripts

AMY	amylose
eros	erosion process
g	gelatinized state
i	species *i*
max	maximum value
n	native state
water	water
ξ	Lagrangian frame
0	initial
1	water component
2	soluble amylose component
3	solid phase component
ODE	ordinary differential equation
∞	asymptotic value

Superscripts

cr	critical value for gelatinization to start
0	intrinsic property
*	properties in gelatinized state

of the existing modelling approaches are empirical and only propose polynomial or power functions linking the extent of soluble and/or insoluble losses to parameters such as cooking time, chemical composition or temperature (Bayram et al., 2004; Sayar et al., 2011; Yadav and Jindal, 2007). Because of their empirical nature, these approaches cannot be extrapolated to a wide range of cooking conditions, nor do they consider the thermal transitions of starch.

A more reliable modelling strategy is to integrate the physical mechanisms underlying the release of the material. A lot of mechanistic approaches describing controlled release in the literature originate in the pharmaceutical sector (Siepmann and Siepmann, 2008). The material release process in a dilute aqueous solution can be explained by two modes: diffusion (sometimes with a dissolution step) and surface erosion. Drug diffusion from a polymeric matrix is commonly described by Fick's law (Barba et al., 2009; Brazel and Peppas, 2000; Lamberti et al., 2011). Dissolution is the process by which solute becomes surrounded by solvent particles. To account for this phenomenon, Zhang et al. (2003) added a source term in the mass balance equation. In the case of cooking rice, only a few models consider the release of material by diffusion. By considering rice grain as a binary mixture of starch and water, Davey et al. (2002) only solved the water transport equation. However, the absence of a proper starch transport equation means the model is incomplete. Modelling material release and water uptake simultaneously is equivalent to solving a diffusional mass transport problem including consideration of the convective effects between species. For example, this approach was used by Bona et al. (2007) to model salt transport during cheese processing.

Surface erosion occurs in drugs with low water solubility, which is partly the case of the starch in rice. Katzhendler et al. (1997), Zhang et al. (2003) and Lamberti et al. (2011) modelled erosion of the surface of polymers by introducing an erosion rate constant or velocity, assuming a zero-order kinetic process. Despite microscopic observations of cooked rice and the suggested occurrence of surface erosion (Briffaz et al., 2012), this phenomenon has not been modelled in rice cooking to date.

We previously developed a physically-based rice cooking binary model (Briffaz et al., 2014a) able to describe and predict mass transport in a swelling and gelatinizing rice grain. The aim of the present study was to upgrade this model by adding diffusion of soluble amylose with counter current convective effects of water and surface erosion occurring during rice cooking. Predicted mean water and amylose contents and erosion rates were compared to experimental data.

2. Model concept and basic principles

Fig. 1 shows an adaptation of the theoretical concept of rice grain water uptake depending on whether the starch is native or gelatinized (Briffaz et al., 2014a), considering soluble amylose

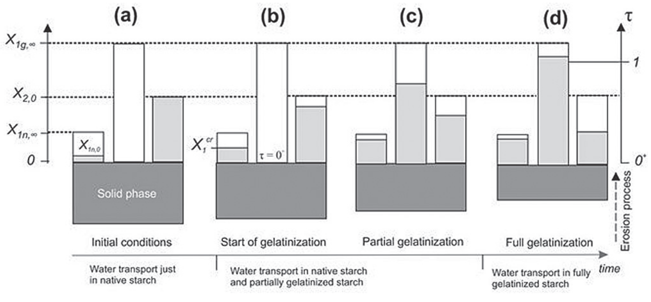

Fig. 1. Schematic diagram describing rice grain water uptake (X_1), amylose leaching (X_2) and solid phase surface erosion during cooking. **(a)** and **(b)**: Native starch X_{1n} absorbs water with a potential $X_{1n,\infty}$ until it reaches X_1^{cr}; **(b)** and **(c)**: Starch starts to gelatinize ($\tau = 0^+$) and takes up excess water X_{1g} with a potential $X_{1g,\infty}$. Soluble amylose starts to leach out of the grain from its initial value $X_{2,0}$ **(d)**: fully gelatinized state ($\tau = 1$). Soluble amylose continues to diffuse in the cooking water.