Modelling of water transport and swelling in a single rice grain during cooking: impact of starch gelatinization

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Starchy food texture has a strong dependency on gelatinization and water content distributions (1). A physically-based model was designed to predict cooked rice sensory attributes.

Keywords: modelling, swelling, gelatinization, starch, texture.

Mathematical model (COMSOL Multiphysics™)

The present binary model (1: water; 2: anhydrous starch) includes (figure 1):

- Water transport with two water populations: in native X_{1n} and gelatinized starch X_{1g} (kg/kg db):

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

where ξ and r are the Lagrangian and Eulerian coordinates respectively (m), D_i are the apparent diffusivities ($m^2.s^{-1}$), X_1^{cr} is the water content threshold for gelatinization starting-up (kg/kg db) and ρ_i are the densities of the species i (kg.m^{-3}).

- Starch gelatinization: local degree of starch gelatinization τ is a function of temperature and local water content within rice (figure 2).
- Swelling using an Arbitrary Lagrangian–Eulerian method: $\rho_2 r^2 dr = \rho_2^0 \xi^2 d\xi$
- Model validated for 3 steeping temperatures (50, 75 and 95°C), through 3 independent ways:
  - Water uptake (gravimetry) (figure 3)
  - Volumetric change
  - Gelatinization front kinetic (polarized light microscopy) (figure 4)

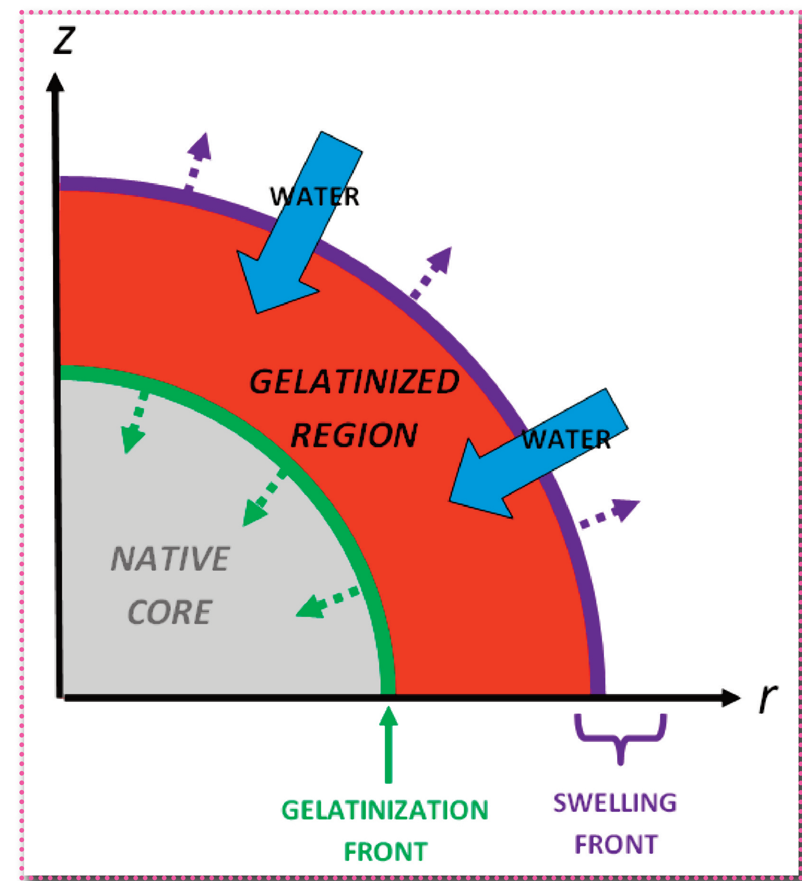

Figure 1. Modelled phenomena involved during rice cooking.

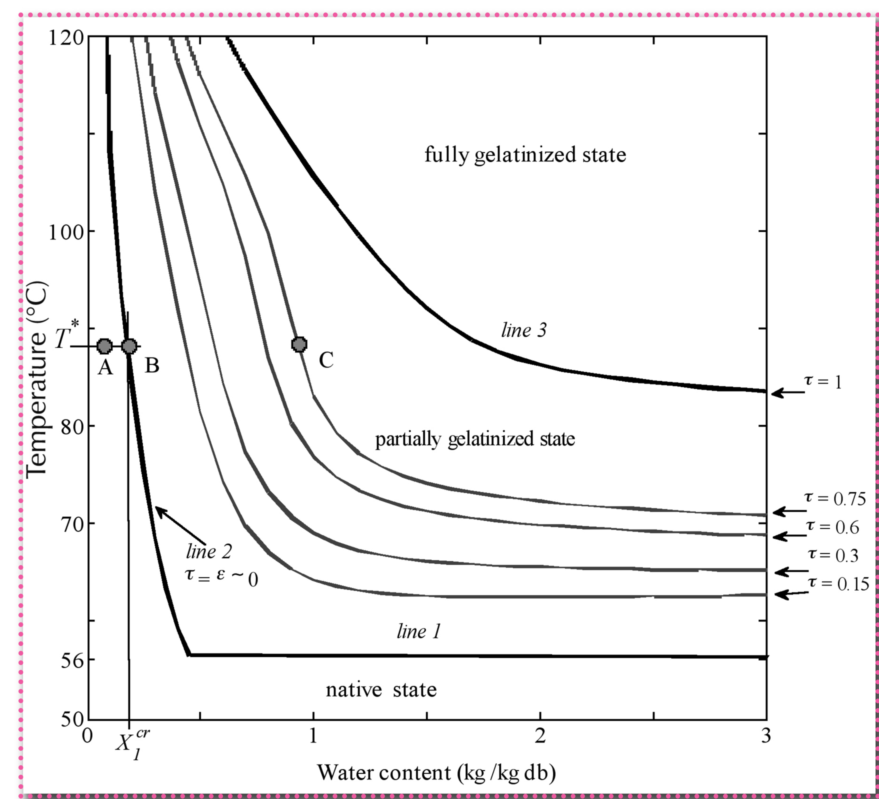

Figure 2. State diagram of rice starch-water mixtures (A: native state, B: gelatinization starting-up, C: 75% gelatinized starch).

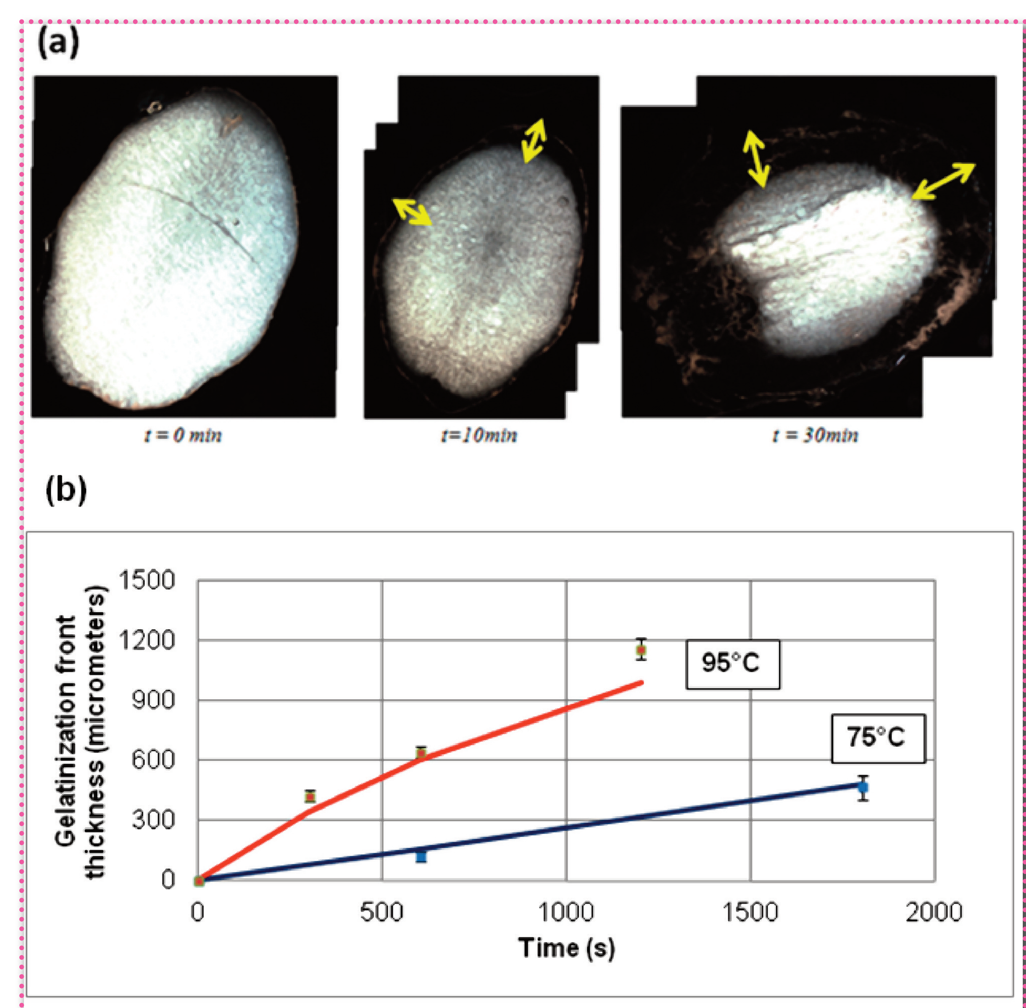

Figure 4. Gelatinization front kinetics: (a) polarized light microscopy at 75°C in excess water; (b) Comparison model / experimental data at 75°C and 95°C.

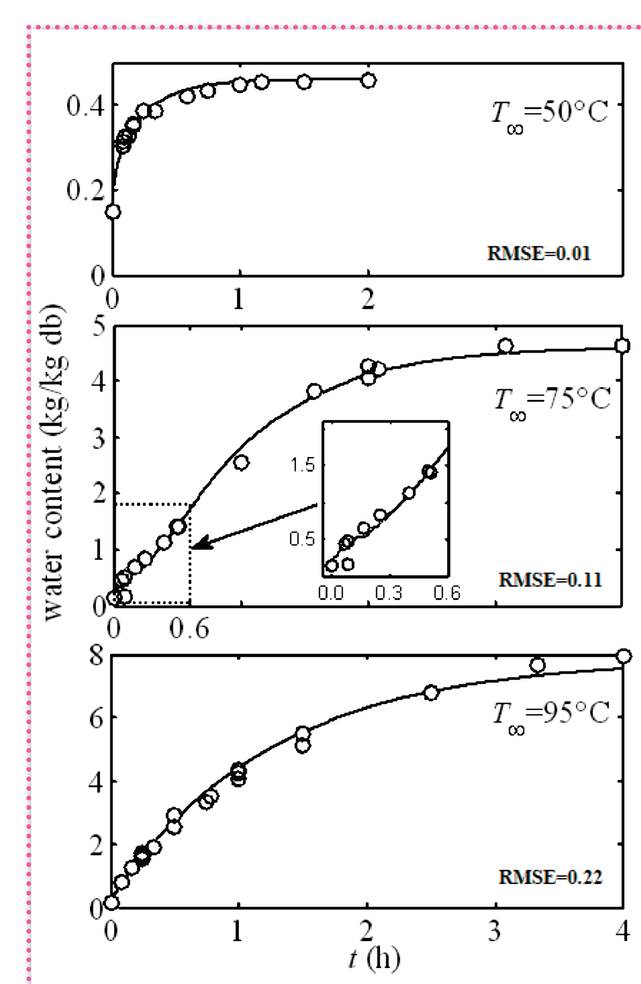

Figure 3. Water uptake kinetics (kg/kg db) in excess water at 50°C, 75°C and 95°C.

Model application: Texture prediction from simulated profiles

- Four limited-water rice cooking programs (namely 1, 2, 3 and 4; figure 5) were run with a rice cooker (picture) and subjected to sensory evaluation (firmness and crunchiness).
- Cooking programs also simulated to obtain the final degree of starch gelatinization and water content profiles. Programs 1 and 2 resulted in remaining low-hydrated native regions whereas programs 3 and 4 led to highly-hydrated and fully gelatinized grain (figure 6). The native and low-hydrated core may confer more firmness and crunchiness.

COOKING PROGRAMS			AVERAGE SENSORY ATTRIBUTE SCORE	
PRECOOKING	COOKING LEVEL	PROGRAM NUMBER	Firmness	Crunchiness
No	Low	1	8.3[a]	3.2[a]
Yes	Low	2	6.1[b]	2.7[ab]
No	High	3	7.0[b]	3.3[a]
Yes	High	4	5.1[c]	2.1[b]

Figure 5. Limited-water cooking programs and their respective average firmness and crunchiness sensory scores.

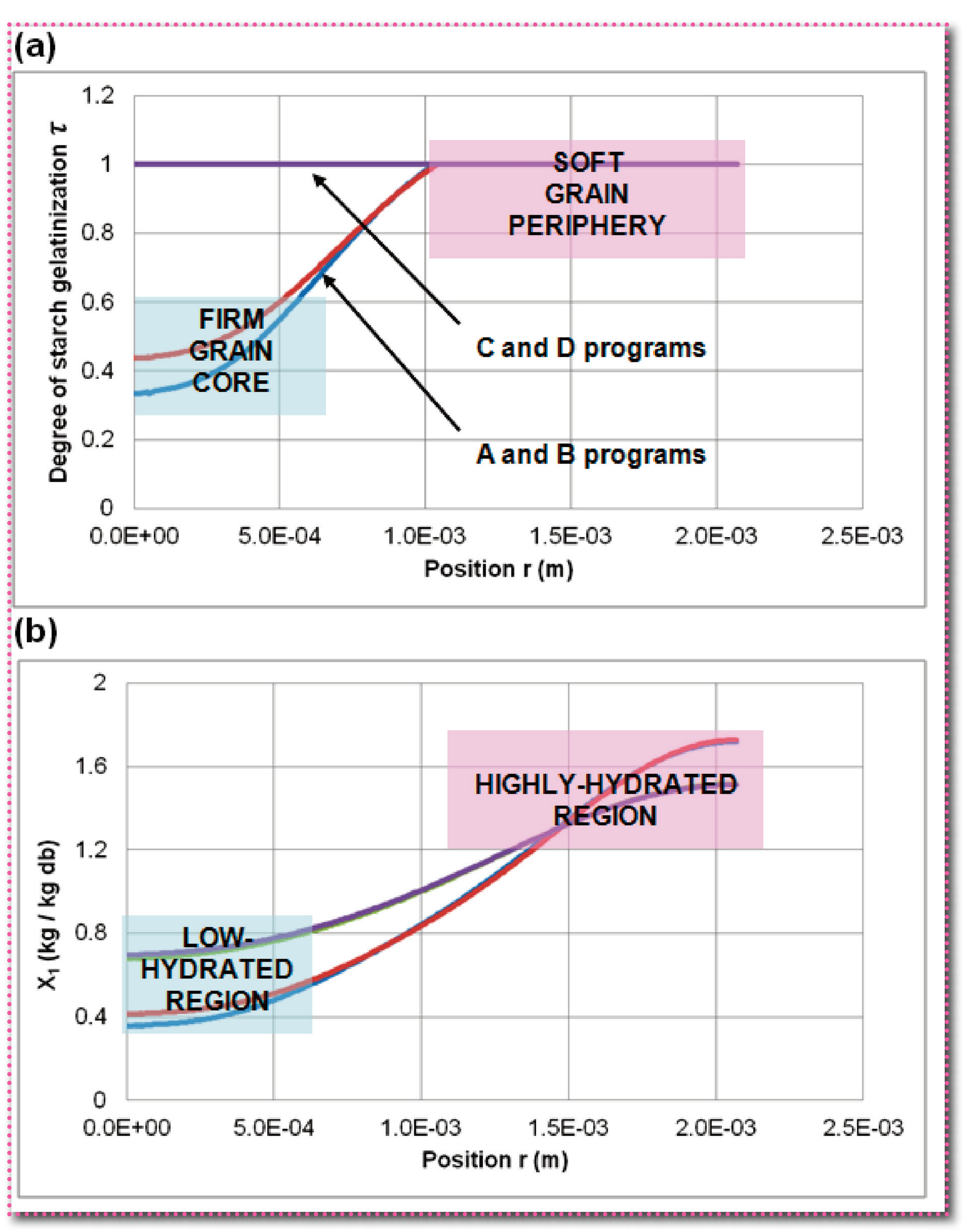

Figure 6. (a) Degree of gelatinization (τ) and (b) water content (X_1) profiles at the end of the four cooking programs.

Conclusion

This new "mechanistic" modeling approach can predict the local extent of two major phenomena (water transfer and gelatinization) involved in rice cooking process. This opens new ways for cooking process optimization.

Reference

1. Irie, K., Horigane, A.K., Naito, S., Motoi, H., Yoshida, M., (2004). Moisture distribution and texture of various types of cooked spaghetti. Cereal Chemistry 81(3), 350-355.

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