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Experimental analysis and finite element simulation of the hydration process of barley grains

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ABSTRACT

Barley grains were hydrated under different conditions of temperature, from 10 °C to 25 °C, during 32 h. The average moisture content of the grains was increased from 0.16 ± 0.01 kg/kg to 0.85 ± 0.12 kg/kg. A theoretical model that represents the phenomena of heat and mass transfer which takes place during the process was developed and solved using the finite element method, considering a three-dimensional geometry and thermophysical properties dependent on moisture content. Given that the model adequately represented the experimental data, it can be used to simulate and design hydration processes of cereals allowing reduction of time and costs.

1. Introduction

Barley (*Hordeum vulgare* sp. *Vulgare*) is one of the most important cereals grown worldwide and it is mainly used in the production of malted flour or flakes for bakery products and dietary formulation of animal feed. Approximately 90% of the barley production is destined to malting due to the firm texture of the grains, the presence of bark, which protects the grain during the germination process, and the traditional beer brewing (FAO, 2004). The maintenance of the germination potential of the grains after harvest is essential to the viability of the malting process (Jacobsen et al., 2002).

Hydration is the first stage of the malting process, followed by germination, drying and grinding of the grains. In this context, the application of barley in the beverage industry requires low initial moisture content, around 13% w.b., 9–12% of protein, average grain size, rather brittle and free of dirt. Grains must also contain enzymes that modify the endosperm. After hydration, a moisture content of around 40% w.b. is desired (Mayolle et al., 2012). Therefore, it is important to understand the hydration kinetics, as well as the influence of process conditions on the incorporation of water (Oliveira et al., 2013; Maskan, 2002). The grain hydration is governed by factors such as the concentration gradient between food and hydrating solution, temperature, pressure, contact area between water and seeds and processing time. Manipulating these factors, it is possible to control the water absorption by the product (Maskan, 2002).

Models such as Peleg, Weibull and first order kinetics are often applied to predict the behavior of grains during hydration. However, considering that these are empirical models based on fitting to sets of experimental data, the results are limited to the laboratory conditions used. For this reason, phenomenological models are increasingly being chosen in order to represent the phenomena involved in the food processing. The use of computational techniques and numerical modeling can be applied to the design of process parameters, with consequences on the profile of moisture content of the cereals being hydrated (Bakalis et al., 2009; Shanthilal and Anandharamakrishnan, 2013; Wang et al., 2011). The mathematical model developed in this work, being based on the numerical solution of Fourier's and Fick's Laws, is of general application: it can be used for experimental conditions that were not tested experimentally and also for other grains, generating substantial savings in time and costs with experimental tests. Another important contribution of this work is the determination of thermophysical properties of barley – density, specific heat, thermal conductivity and thermal diffusivity – in a wide range of moisture contents. These properties may be used in order to design thermal processes of barley, which is relevant given the scarce data

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about physical characteristics and hydration capacity of barley in the literature.

Given the above, the goal of this work is to model and simulate the phenomena of heat and mass transfer during hydration of barley grains in order to evaluate the influence of process temperature on the water absorption and to determine the time required to obtain the desired moisture content.

2. Material and methods

Grains of barley from the cultivar BRS ELIS were donated by Cooperativa Agroindustrial Guarapuava (Paraná, Brazil). This cultivar, harvested in 2011, was cultivated in southern Brazil.

2.1. Chemical composition

The evaluation of the chemical composition of barley was conducted according to the method 925.10 of the Association of Official Analytical Chemists (AOAC, 1995). The moisture content was determined by the gravimetric method at 105 °C, the protein content was obtained by the Kjeldahl method, fat and ash contents were determined by extraction and Soxhlet incineration in a muffle furnace at 550 °C, respectively, and the contents of starch and dietary fiber were obtained by acid hydrolysis followed by polarimeter reading (Polax, model WXG-4) and by an enzymatic method, respectively.

2.2. Hydration process

Hydration tests were conducted for 32 h in a thermostatic bath (Quimis, model Dubnoff Q226M2) with stirring and temperature control. In each experiment 250 g barley grains samples were immersed in beakers containing distilled water. The experiments were performed in duplicate for each temperature, and moisture content was analyzed for two samples of each test, resulting in four samples collected in each analysis time. Right after collection of the samples, their surface water was removed with a paper towel.

The hydration temperatures used were 10, 15, 20 and 25 °C. The moisture content of the barley samples was determined in quadruplicate (AOAC, 1995) at time intervals of 0, 0.08, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 5, 6, 7, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30 and 32 h.

2.3. Modeling and simulation of the hydration process

The mathematical model used to represent the phenomena of heat and mass transfer during hydration of barley was constructed based on the laws of Fourier and Fick, respectively, according to Eqs. (1) and (2). The computational domain is represented in three dimensions by Fig. 1.

$$\rho Cp\frac{\partial T}{\partial t} + \rho Cpu\nabla T = \nabla(k\nabla T) + Q \tag{1}$$

$$\frac{\partial U}{\partial t} + \nabla(-D\nabla U) = R \tag{2}$$

where ρ, Cp and k are the barley density (kg/m^3), specific heat (J/kg K) and thermal conductivity (W/m K), respectively, T is the grain temperature (K), u is its velocity field (m/s), U is the moisture content d.b. (kg/kg), Q is the heat generation (W m), D is the mass diffusion coefficient (m^2/s) and R is the mass generation or consumption (kg/m^3).

The following assumptions were considered for the construction of the numerical model:

- Null speed field of the barley grains.
- Null thermal generation.

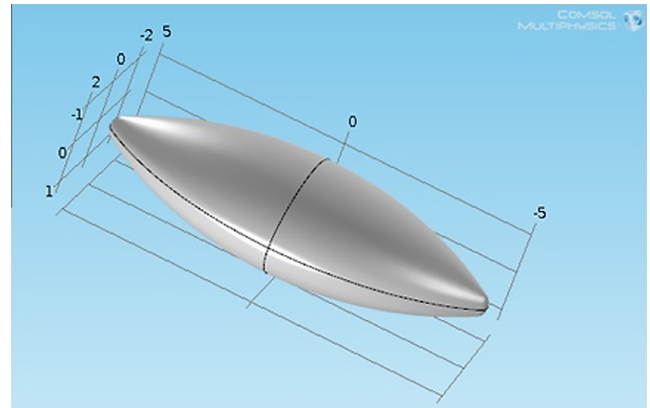

Fig. 1. Computational domain.

Table 1
Chemical composition of barley.

Component	Concentration (%)	References (%) *
Moisture	11.89 ± 0.06	11–13
Fats	2.20 ± 0.04	3–4
Proteins	9.38 ± 0.06	9–14
Starch	58.05 ± 0.64	53–67
Ashes	1.74 ± 0.08	2–3
Dietary fiber	17.32 ± 0.00	14–25
β-glucan	4.34 ± 0.04	3–7

* Range of values found by Aman and Newman (1987), Oscarsson et al. (1996) and Andersson et al. (1999).

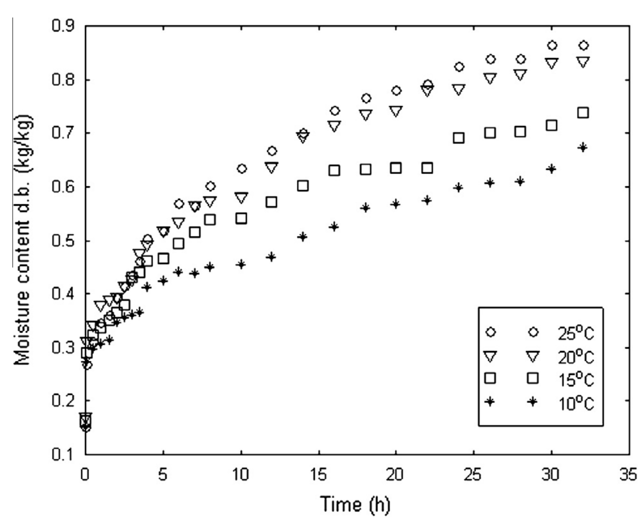

Fig. 2. Moisture content of barley during hydration.

- Null mass generation and consumption.
- Thermophysical properties homogeneous along the grain, but variable with time.
- Initial moisture content and temperature homogeneous.

The following mathematical model, written in generalized coordinates, was obtained applying the previous conditions to Eqs. (1) and (2).

$$\rho C_p\frac{\partial T}{\partial t} = \nabla(k\nabla T) \tag{3}$$