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Drying–toasting kinetics of presoaked soybean. A mathematical model considering variable diffusivity, shrinkage and coupled heat transfer

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ABSTRACT

In this work, the kinetics of drying–toasting of presoaked soybean in fludised thin layer at air temperatures between 100 and 160 °C was mathematically modeled. A two-stage shrinkage model was developed, which relates soybean radius with the average moisture content. Spherical geometry was assumed with radial diffusion, and a local mass balance coupled with an overall heat balance in the soybeans was solved by finite difference and the Euler method, respectively. The heat transfer coefficient was estimated from the energy balance using experimental drying rates. Values varied from 176 to 312 W/(m^2 °C). The effective diffusion coefficient was proposed to be a function of temperature and moisture content. The temperature dependence was described by an Arrhenius relationship, while the moisture content dependence, found by extending the shrinkage behavior to a local level. The Arrhenius parameters were estimated by solving an inverse problem for the whole dataset. The activation energy was 51.9 kJ/(mol K), with a pre-exponential factor of 0.0237 m^2/s. Predicted temperatures and average moisture content agreed well with experimental measurements.

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1. Introduction

Soybean (*Glycine max*) is a valuable resource for healthy nutrition for its high content of high quality protein (40% w/w) and unsaturated fatty acids in the oil (20% w/w) (Deshpande et al., 1993; Kashaninejad et al., 2008). In view of this potential and considering the growing consumer demand for the intake of dehydrated ready-to-eat snacks (Sun-Waterhouse et al., 2010), a process was developed (Torrez Irigoyen and Giner, 2011), by which presoaked soybeans were dried-toasted, leading to a stable, low-moisture, crispy product, all features that are desirable for snack type products. Such crispiness is because of the decrease in grain volume experienced during drying–toasting was lower than the increase of grain volume observed along soaking. Furthermore, presoaking could help to improve the inactivation of antinutritional factors (Machado et al., 2008; Osella et al., 1997).

Fluidised bed technology has been successfully used for drying and processing of value-added products such as foods and inorganic particles because it imparts a high degree of mixing and uniform heat transfer (Giner and De Michelis, 1988; Mayor and Sereno, 2004; Senadeera et al., 2006; Nitz and Taranto, 2007).

Drying of biological materials is a complex process due to the simultaneous phenomena of heat and mass transfer which occurs inside each particle. Adequate models are required to describe the mechanism of heat and mass transfer and thus to provide means for understanding the effect of key operating variables on process performance parameters as drying time and process costs (Maroulis et al., 1994; Sander, 2006; Bialobrzewski et al., 2008). Regarding to the energy consumption associated with food drying, there is scarce literature dealing with the interplay between mass transfer and heat transfer in the presence of particle shrinkage (Maroulis et al., 1994; Donsí and Ferrari, 1995; Parmar and Hayrust, 2002).

Mathematical modeling of food drying kinetics has been reported by a number of researchers (Sun and Woods, 1994; Jha, 2005; Khatchatourian, 2012; Nilnont et al., 2011). However, a rigorous diffusion model solved locally considering variable diffusivity and shrinkage, coupled with heat transfer, in a process above

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Nomenclature

a	shrinkage coefficient
a_v	specific grain surface, m^2/m^3
a_w	water activity
C	water concentration, kg/(m^3 product)
C_p	specific heat of grain, J/(kg dry matter °C)
D_{eff}	effective diffusion coefficient of water in soybean, m^2/s
h_T	effective heat transfer coefficient, W/(m^2 °C)
L_g	heat of desorption of water in the grain, J/kg
L_w	heat of vaporization of pure water, J/kg
m_s	dry mass of grains, kg
M_w	molecular mass of water, kg/kmol
R	grain radius, m
r	radial spherical coordinate, m
R_g	universal gas constant, 8.314×10^{-3} kJ/(mol K)
T	grain temperature, °C
t	time, s
T_a	air temperature, °C
W	moisture content, kg/(kg dry matter)

Greek symbols

ρ	particle density, kg/m^3
ρ_{ds}	dry matter density, kg/m^3
ρ_w	water density, kg/m^3

Subscripts

0	initial
e	equilibrium
exp	experimental value
k	Kelvin
m	average
s	surface
sim	simulated value

the boiling point of water for high-moisture soybean constitutes a subject not addressed previously. For simple geometries with constant volume (V) and diffusivity (D_{eff}), the unsteady state diffusion equation has analytical solutions that were successfully employed by several authors (Giner and Mascheroni, 2001; Akpinar, 2006; Kashaninejad et al., 2008; Da Silva et al., 2009). Some authors as Ruíz-Lopez and García-Alvarado (2007) and Ruíz-Lopez et al. (2012) obtained complex analytical solutions considering both shrinkage and variable diffusivity and using a constant average food temperature.

Although experimentation is an essential part for the progress of food drying science and technology, fundamental research carried out with the aid of mathematical modeling and computer simulation provides a powerful tool for investigating the intricate physics occurring during drying of wet materials (Turner and Mujumdar, 1997). Some authors have used complex models that consider simultaneous heat and mass transfer to predict food drying kinetics. They are usually constituted by nonlinear differential equations and require numerical solutions (Misra and Young, 1980; Simal et al., 1996; Jha, 2005; Ramos et al., 2010; Nilnont et al., 2011).

In turn, Torrez Irigoyen and Giner (2014) observed that a constant-volume, constant-diffusivity analytical solution of the unsteady state diffusion equation for spheres during drying–toasting of soaked soybean yielded accurate predictions, despite previous studies by the same authors on density and volume revealed non-negligible shrinkage during drying–toasting (Torrez Irigoyen and Giner, 2011). This unexpected predictive quality may have been caused by constancy of the ratio of diffusion coefficient to radius squared present in the analytical solution (D_{eff}/R^2) and neither of numerator nor denominator during the process. Simal et al. (1996) and Rahman and Kumar (2006) considered that shrinkage is one of the main changes underwent by materials during drying so that it should be accounted for in models to improve their physical significance, i.e., their ability to describe the phenomenon more accurately. For instance, an effective diffusion coefficient determined within a complex model is more meaningful as transport parameter than if derived from a simplified model. To this end, the main objective of this work was to develop a rigorous model for drying–toasting of soaked soybean in fluidised thin-layers, considering volumetric shrinkage, variable effective diffusion coefficient with moisture content and temperature, and compare these predictions with experimental results measured earlier.

2. Material and methods

2.1. Materials

Soybeans variety Don Mario 5.5 i were provided by Don Mario Semillas (Don Mario Seeds Company), Chacabuco, Provincia de Buenos Aires, Argentina. Moisture content of raw soybean at reception was 0.113 kg water/kg dry matter.

2.2. Experimental procedure

Grains were cleaned carefully and then immersed in drinking water using a water to soybean mass ratio of 2:1, and allowed to soak for 24 h at 10 °C. The initial radius of soaked soybean had an average value of 4×10^{-3} m. To facilitate fluidisation of particles at the beginning of drying–toasting, the soaked soybeans were previously surface-dried at 50 °C for 10 min by utilizing an automatically controlled, mechanical convection oven (Torrez Irigoyen, 2013). The drying–toasting experiments were conducted in a purpose-built fluidised bed dryer with automatic control of inlet air temperature and air velocity, the latter value being 2.5 m/s. Further details about the drying–toasting experiments, procedures and techniques can be found in a previous work (Torrez Irigoyen and Giner, 2011, 2014).

3. Mathematical modeling of thin layer drying–toasting

3.1. Microscopic mass balance with diffusional transport of water

Assuming water transport by molecular diffusion, the microscopic mass balance can be expressed as follows (Crank, 1975) for constant volume of grain:

$$\frac{\partial W}{\partial t} = \nabla(D_{eff}\nabla W) \qquad (1)$$

where D_{eff} is the effective diffusion coefficient of water relative to the dry matter. Torrez Irigoyen and Giner (2011) found that soaked soybeans have an almost spherical shape, with a sphericity of 0.96, while the totally dried-toasted soybean have a value of 0.94. So this model assumed spherical shape for the soybean. Considering diffusion coefficient as a function of moisture content and temperature in spherical coordinates and assuming that variations take place

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