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Mathematical modeling of eggplant drying: Shrinkage effect

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ABSTRACT

In this paper two mathematical models with shrinkage effect describing eggplant drying are developed and discussed. The models are both modified diffusion equations and take differently into account changes of eggplant slice structure during drying. In the first model a diffusion coefficient variable with the water content is considered while in the second model a fictitious convective term is introduced. The two models are both suitable to describe the analyzed drying processes. Moreover, their equivalence is analytically demonstrated. Parameters values are estimated through a nonlinear regression procedure by comparison with the drying experiments carried out at different temperatures. Information about thickness evolution, derived from the models, are found to be in agreement with experimental data.

1. Introduction

Eggplants are vegetables whose shelf-life at temperature of 10–15 °C is about 10 days (Hu et al., 2010). The limited shelf-life constitutes a heavy drawback for commercial purpose. Several studies deal with the possibility of prolonging shelf-life (Arvanitoyannis et al., 2005; Hu et al., 2010; Jha and Matsuoka, 2002; Wu et al., 2008, 2009; Zhang and Chen, 2006), using several techniques. Since they are common ingredients in preparation of dry long-life mixtures, the shelf-life can be profitably prolonged through drying.

Drying is a very important technology to improve food preservation (Sagar and Kumar, 2010). Moisture's removal preserves foods from deterioration due to growth of microorganisms (Ansari and Datta, 2003), action of enzymes, and oxidation's reactions (Raitio et al., 2011). Moreover, it provides lighter weight and smaller volumes for transportation and storage. Common applications of drying technologies are in use for various vegetables conservation. In some cases vegetables are consumed dried (e.g. dried fruits) or rehydration is delegated to the end consumers as in dry soups.

The main objective to be reached during drying is to keep almost constant the nutritional and organoleptic properties. Moreover, many parameters (e.g. color, texture, global aspect, roughness) influence the overall aspect of the end product, and therefore the consumer acceptability. These properties depend widely on drying conditions.

From this viewpoint, the development of suitable mathematical models, providing temporal evolution of state variables, is a matter of practical interest to achieve the optimal process conditions for extending shelf-life of product. In literature several studies investigating industrial drying processes of vegetables, supported by mathematical models, are available. They are mainly based on two different approaches: theoretical or empirical (Datta, 2007a,b). Theoretical models are generally based on Fick's second law of diffusion and were usefully applied for drying processes of many food products such as rice (Basunia and Abe, 2001), hazelnut (Ozdemir and Devres, 1999), Amelie mango (Dissa et al., 2008), rapeseed (Crisp and Woods, 1994), and potato (Akpinar et al., 2003). Despite of computational drawbacks, they provide useful information about physical mechanisms involved in drying process and assure good predictions of temporal evolution of state variables when the process conditions change. Moreover, they are often exploitable in a wide class of food products.

In contrast, empirical models are either derived by series expansions of theoretical models' general solutions or, more often, are pure kinetic formulas depending on process conditions. The empirical models are easy to deal with, but they do not provide any physical information and their use is restricted to specific process conditions. The most widespread empirical models in literature are those of Newton, Page, Henderson and Pabis, Wang and Singh (Akpinar and Bicer, 2005; Ertekin and Yaldiz, 2004), and were applied to the description of several aspects of drying processes (Khalloufi et al., 2009, 2010) for many foodstuffs e.g. quince (Koc et al., 2008), eggplant (Doymaz, 2011; Ertekin and Yaldiz, 2004), cherry tomato (Heredia et al., 2007), apricot (Togrul and Pehlivan,

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Nomenclature

Used notations are reported in the following.

c	differential dimensionless water content at the position x and time t
$d(c)$	diffusion coefficient (function of c) (cm^2/s)
D	effective diffusion coefficient (constant) (cm^2/s)
G	equilibrium constant
h	mass transport coefficient (1/cm)
K_m	overall mass transfer coefficient (1/cm)
L	eggplant slices thickness (cm)
m	mass of the differential element at the position x and time t
M	total dimensionless water content
n	number of experimental data
P	absolute pressure (Pa)
r	pore radius (μm)
S	surface area of the sample (mm^2)
t	time (s)
T	temperature
u	shrinkage velocity (cm/s)
u_s	estimated mean value of shrinkage velocity (cm/s)
x	spatial coordinate (cm)
β	slope of $d(c)$ (cm^2/s)
γ	surface tension (dyne/cm)
δ	intercept of $d(c)$ (cm^2/s)
ε	void fraction
ϑ	contact angle (°)
v	volume of water per unit area (mm)
ξ	parameter linking u and the spatial derivative of c (cm^2/s)

Subscripts

0	initial value
∞	final value
b	basis
g	gas phase
l	lateral

Superscripts

^	numerical derived value

2003), mushroom (Hernando et al., 2008), and black tea (Panchariya et al., 2002).

Air-drying of food materials is often followed by physical and chemical changes which dramatically influence the process itself (Senadeera, 2008). One of the most important consequences of these changes is shrinkage: a volume reduction, coupled with shape and porosity changes and hardness increase. Such phenomena could also be followed by surface cracking. Another negative effect of shrinkage is, for instance, the reduction of rehydration capability as demonstrated by several authors (Jayaraman et al., 1990; Mcminn and Magee, 1997a,b). Therefore, shrinkage has to be avoided because such physical changes contribute in general to reduce the quality perceived by the end consumer of dehydrated products, traditionally consumed fresh. Obvious exceptions are represented by foods, like dried plums and dates, usually eaten shrunken.

Since shrinkage influences drying and consequently rehydration, it has to be taken into account in mathematical modeling of such processes. Several types of models predicting volume changes are available in literature as, for example, reviewed by Khalloufi et al. (2009), Mayor and Sereno (2004).

Based on two different approaches, two different mathematical models for isothermal eggplants air drying, based on Fick's second law of mass diffusion, are here developed and discussed. Parameters of the models are calculated on the basis of isothermal experimental data at different temperatures, by means of a suitable developed nonlinear regression algorithm. The models provide useful information about shrinkage phenomena supplementing that obtained through experiments.

2. Materials and methods

Drying experiments are conducted on slices of eggplants (*Solanum Melongena*, Longo cultivar). Vegetables are washed and peeled. Cylindrical slices with diameter of 30 mm and thickness of 6 mm are prepared sampling the material from the whole vegetable using a suitable steel mould. The initial water content (kg/kg on dry-weight basis) is 12.704 ± 0.04. Dehydration procedure is the following: eggplant slices are placed over a metal grating in a convective oven (mod. Zanussi FCV/E6L3) operating at constant temperature. Drying experiments are carried out at temperatures 40, 50, 60, 70 °C. These temperatures are usually used in food industries. At suitable time intervals some slices are removed from the oven and their weight loss is measured by means of a digital balance (mod. Gibertini E42, Italia). The procedure is repeated until the weight remains constant for 30 min. This corresponds to drying time of 270 min at 40 °C, 225 min at 50 °C, 165 min at 60 °C, e 135 min at 70 °C.

The pore structure of eggplant samples is analyzed by mercury intrusion porosimetric technique with the instruments Pascal 140 and Pascal 240 (Thermo Finnigan) operating in the pressure range from sub ambient up to 200 MPa. The technique is based on the mercury property to behave as non-wetting liquid with a lot of solid materials. Thanks to this property, mercury penetrates through the open pores of a solid sample under the effect of an increasing pressure. The relation between the pore size and the applied pressure, assuming the shape of pores is cylindrical, is expressed as:

$$P \cdot r = -2\gamma\cos\vartheta \tag{1}$$

where r is the pore radius, γ the Hg surface tension, ϑ is the contact angle and P is absolute applied pressure. Eq. (1) is the well-known Washburn equation (Washburn, 1921). It provides a simple and convenient relationship between applied pressure and pore size. Pore size distributions are therefore obtained generated by monitoring the amount of non-wetting mercury intruded into pores as a function of the increasing applied pressure.

The pressure range investigated allows to cover the pore diameter range from 0.0075 up to 100 μm. Thus, the pressure is sufficient to ensure intrusion of mercury in most of the mesopores (0.002–0.05 μm) and of the macropores (0.05–100 μm). However, majority of the micropores would remain not intruded.

Values of 141.3° and 480 dyne/cm are used for the contact angle and mercury surface tension, respectively (Chesson et al., 1997; Karathanos et al., 1996). Tests are carried out on fresh and dried eggplant samples. Mercury intrusion porosimetric tests are carried out in triplicate to ensure adequate accuracy of the results.

In order to study the effect of the different drying conditions on structural changes occurring also on length-scales greater than 100 μm, the microstructure of dried samples is analyzed using SEM technique. Eggplant samples are coated with a thin layer