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Derivation of two layer drying model with shrinkage and analysis of volatile depletion during drying of banana

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A B S T R A C T

An existing two layer evaporation/diffusion model of thin layer drying was modified to incorporate shrinkage. The model was developed and tested for a heat pump test dryer using cylindrical slices of banana, which were dried as a single layer. Shrinkage and drying data were collected over a range of conditions from 28 to 38 °C and 12–30% relative humidity. In addition, models of depletion of key aroma volatiles were developed, to allow prediction of aroma profiles under different drying conditions. It was found that inclusion of shrinkage significantly improved the goodness of fit of the drying model, with shrinkage in the direction of slice thickness found to have a greater effect on drying rates than shrinkage in the radial direction. Aroma profiles were compared at different drying intervals, using four banana flavor compounds as indicators. Volatile depletion during drying was found to approximate a first order kinetic reaction with exponential decay over short periods.

1. Introduction

Drying of food products has been used for centuries to improve food stability. Conventional dryers pass hot air through a product to remove moisture. For commercial food drying applications, it is often necessary to estimate drying times quickly from limited data, and as a result, drying models must be as simple yet as accurate as possible. For food products, the dominant period is normally the falling rate period, in which the product dries towards equilibrium with the drying air (Sahari and Driscoll, 2013), and so most efforts at modelling product drying concentrate on this region. Shrinkage is defined as the ratio of product volume during drying to the initial product volume, and all food products undergo some dimensional modification during the drying process (Hatamipour and Mowla, 2002). Shrinkage may also affect the heat and mass transport properties, in particular the heat and mass diffusivities, the product surface area and the distance for molecular diffusion. Thus shrinkage must influence the overall drying rate (Suarez and Viollaz, 1991).

There are many thin layer drying models in the literature, ranging from simple single term model to finite element models of great complexity. Both the single and two compartment models popular in the literature can be derived from series solutions to Fick's second law of diffusion for regular shapes, and so are fundamentally diffusion models. Most simple models are derived from integral forms of the compartment models by assuming constant aeration conditions (temperature and relative humidity) and therefore are not applicable to situations where air quality changes during drying, as happens in a commercial dryer. The two layer model used in this paper was developed to describe the drying behaviour of the product under changing aeration conditions. Since shrinkage was not initially included in this model, the immediate goal was to develop the simplest variation of this model which would incorporate changes in product shape during drying.

The two layer model includes both diffusion and surface evaporation. Under constant drying conditions the two layer model described below defaults to a similar form to the two term drying model (Wu et al., 2012). A product is modelled as an outer layer (in contact with the drying air) and an inner layer (which can only interact with the outer layer). Both layers are considered isotropic in properties, and do not correspond to real physical layers (such as

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pulp and skin).

Define a mass ratio μ as the dry solids mass ratio between the outer and inner layers:

$$\mu = \frac{m_{s2}}{m_{s1}} \tag{1}$$

where m_s is the layer dry mass. From Fick's first law of diffusion, moisture movement from layer 1 to layer 2 can be expressed as:

$$\frac{dM_1}{dt} = -k_1 \mu (M_1 - M_2) \tag{2}$$

Including both diffusion from the inner layer and surface evaporation gives:

$$\frac{dM_2}{dt} = -k_1(M_2 - M_1) - k_e(M_2 - M_e) \tag{3}$$

The factor μ in equation (2) ensures mass is conserved at the layer interface. The drying constants k_1 and k_e are assumed to vary with temperature with an Arrhenius-type dependency (Palipane and Driscoll, 1994):

$$k_1 = k_{10} \exp\left(-h_1/R_G T_k\right) \tag{4}$$

$$k_e = k_{e0} \exp\left(-h_e/R_G T_k\right) \tag{5}$$

From mass balance, the average moisture content of the product is:

$$M = \frac{m_{s1}M_1 + m_{s2}M_2}{m_{s1} + m_{s2}} = \frac{M_1 + \mu M_2}{1 + \mu} \tag{6}$$

Integration of this model for constant conditions gives an equation similar in form to the two compartment model, but with one less constant.

Many researchers have developed shrinkage models for specific products, as functions of moisture content. Linear empirical models have been developed for several fruits and vegetables, for example apple and carrot (Ratti, 1994) and potato (Wang and Brennan, 1995). Non-linear behaviour has been observed at low moisture contents, which might be due to loss of plasticity, creation of internal vacuoles and/or differential shrinkage effects. Non-linear empirical models have been developed to describe the behaviour of such food products (Lozano et al., 1983; Ratti, 1994), but due to their specific and empirical nature, application of these models is difficult.

The linear region of shrinkage with moisture may be called the isotropic region, not meaning homogeneous throughout, but rather uniform in all directions, since differential shrinkage between the inner and outer regions of the product must still be considered. Theoretical shrinkage models, called the uniform drying model, the semi-core drying model and core drying model, were proposed and tested with experimental shrinkage data for root vegetables (Kilpatrick et al., 1955; Suzuki et al., 1976). The most successful shrinkage model for the isotropic region has been a simple model based on volume additivities of the different components in a product (Mayor and Sereno, 2004; Perez and Calvelo, 1984; Rahman and Potluri, 1990), which assumes that the change in product volume is the same as the volume of moisture removed during drying:

$$V_0 - V = \Delta m_w/\rho_w \tag{7}$$

$$S = V/V_0$$

Based on these relations, Perez and Calvelo (1984) derived the linear shrinkage model:

$$S = \frac{1}{1-\varepsilon}\left[1 - \frac{\rho_a}{\rho_w}\cdot\frac{M_0 - M}{1 + M_0}\right] \tag{8}$$

where ε is the internal porosity developed during the drying process, M_o is the initial moisture content, ρ_a is the apparent density of the product, ρ_w is the density of water. Mayor and Sereno (2004) suggested that shrinkage almost entirely compensates for moisture loss while the product is in a rubbery state, but that at low moisture content, the material transforms to a glassy state, the rate of shrinking is reduced and non-linear behaviour becomes apparent. For this reason the model suggested here is only valid at moistures where the product is in a plastic state.

Shrinkage is rarely included in published drying models. However the process for doing so has been described by Bear (1991), and involves firstly the construction of a conceptual model of shrinkage in terms of product dimensions and moisture content, and secondly incorporation into the drying model. Queiroz and Nebra (2001), who also worked on banana shrinkage drying models, assumed an infinite cylinder and expressed shrinkage in terms of the dimensionless radius $\frac{R}{R_0}$. This was assumed to be linearly related to moisture content:

$$\frac{R}{R_0} = A + BM(t) \tag{9}$$

where A and B are constants. Karim and Hawlader (2005) developed a drying model for banana which included shrinkage, but modelled the product as a thin slab at uniform temperature and moisture content. The material surface was considered as shrinking at a velocity (u), which was analogous to the convective flow of moisture transfer, and the shrinkage effect was incorporated into calculation of the diffusion coefficient by analogy with Crank's solution to the diffusion equation (Gekas and Lamberg, 1991):

$$\frac{\partial M}{\partial t} + u\frac{\partial M}{\partial x} = D_{eff}\frac{\partial^2 M}{\partial x^2} \tag{10}$$

$$\frac{D_{ref}}{D_{eff}} = \left(\frac{b_0}{b}\right)^2 \tag{11}$$

Some other examples of shrinkage modelling of product drying are potato (Fusco et al., 1991), grapes (Azzouz et al., 2002), apple (Golestani et al., 2013), mango (Hernandez et al., 2000) and soybean (Misra and Young, 1980). For the purposes of the current study, shrinkage models based on intensive numerical solutions were rejected, as modification to the drying model would then lead to an unwieldy model. Since a simple yet accurate model of shrinkage exists (at least for the isotropic region), this was chosen for inclusion in the two layer drying model.

Even for isotropic shrinkage, however, many products have a "thinnest" dimension, which has the greatest effect on the drying rate as water molecules have less distance to diffuse to reach the product surface. Since moisture is removed from the product outer surface first, shrinkage must proceed from the outer surface towards the product centre.

Aroma volatiles will behave in a similar way, but with the added complication that moisture can act as a transport mechanism