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Estimation of effective diffusivity of pear tissue and cuticle by means of a numerical water diffusion model

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Abstract

An estimation procedure of effective diffusivity in pear tissue by means of a numerical water diffusion model is presented. Conference pears (*Pyrus communis cv.* Conference) of different picking date and different storage period and temperature were investigated. The moisture diffusivity of different tissues like outer cortex, inner cortex and cuticle was estimated. Results showed that the effective diffusion coefficients of water are slightly larger in late picking date pears than those of early picking date, but the effect of storage time was unclear and a large biological variability was observed. Temperature had different effects on the different tissues. The diffusion coefficients increased by a factor 2 in case of cuticle and by a factor 3.6–9.6 in the case of inner cortex tissue when the temperature increased from 1 °C to 20 °C. The value of the diffusion coefficient decreased dramatically from inner cortex tissue ($123.0\times10^{-13}\ m^2\,s^{-1}$ at 1 °C; $435.9\times10^{-13}\ m^2\,s^{-1}$ at 20 °C) to outer cortex tissue ($5.3\times10^{-13}\ m^2\,s^{-1}$ at 1 °C; $10.5\times10^{-13}\ m^2\,s^{-1}$ at 20 °C) and cuticle ($0.55\times10^{-13}\ m^2\,s^{-1}$ at 1 °C and $1.28\times10^{-13}\ m^2\,s^{-1}$ at 20 °C). These values are comparable with those in literature obtained for other horticultural products such as apple.

Keywords: Continuum; Sorption isotherm; Moisture transfer; Diffusion; Cuticle; Pear

1. Introduction

In fruits, water is one of the most important components to provide in their metabolic, nutritional, physiological and biochemical needs. The water content in plants varies according to species, tissue and cell type and is also dependent on ambient and physiological conditions (Merva, 1995).

Moisture transport in fruit has been modelled by means of Fick's second law of diffusion. Three mechanisms are often considered most dominant in foods in general: convection (Darcy flow), molecular diffusion and capillary diffusion (Datta & Zhang, 1999). They differ according to the driving force, which causes the movement. Convection occurs by a pressure difference. The second mechanism is driven by a concentration difference. The last mechanism is due to the difference between the relative attraction of the molecules of the liquid for each other and for those of the solid. Moisture transport studies in conventional heating and conventional drying often use an effective diffusivity model encompassing all these terms to some extent (Datta & Zhang, 1999). In fruit, transport also occurs by osmosis. Osmosis is a combination of pressure and diffusion flow across selective cell membranes (Finkelstein, 1987). The continuum approach to mass transfer is the simplest means to describe moisture diffusion in fruit tissue because it avoids the necessity of modelling the

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microscopic pore space. It constitutes a phenomenological approach as the mass transfer coefficients that appear in the macroscopic balances have to be determined experimentally. However, such models, in which moisture fluxes are expressed in terms of water concentration gradients, hide the complex water relations and underlying transport processes in the cellular tissue (Datta, 2002). Clearly, water content alone is insufficient to describe water status and movement in fruit, in relation to cellular disorders that result in quality loss (Nguyen, Verboven, Daudin, Vandewalle, & Nicolaï, 2004).

In literature, the published data of moisture diffusivity in food products present a huge variability and the values vary from 10^{-12} to 10^{-8} m^2/s (Zogzas, Maroulis, & Marinos-Kouris, 1996). This variability depends on the types and conditions of experimental procedures used for determination of the moisture diffusivity, data treatment methods (Zogzas & Maroulis, 1996) as well as on the product properties (composition, physiological state, heterogeneity of the structure) (Gou, Mulet, Comaposada, Benedito, & Arnau, 1996).

Moisture diffusivity in solid foods can be determined by different methods involving defined geometries, and well-defined experimental conditions (steady state or transient conditions). The methods, which have been used to estimate water diffusivity are based on drying kinetics, sorption or desorption kinetics, and moisture profile analysis (Crank, 1975; Doulia, Tzia, & Gekas, 2000; Gros & Ruegg, 1987; Zogzas & Maroulis, 1994). The most frequently used methods for moisture diffusivity for solid foods are briefly presented here.

1.1. Permeation method

A thin sheet of solid is kept in between two compartments which are conditioned at constant but different humidity and temperature. After a certain time, a steady state is reached and a constant linear concentration gradient is developed in the material and the surfaces of the thin sheet are assumed in equilibrium with the diffusion source. The diffusivity (or permeability) is deduced from an observed value of the rate of moisture transfer (by a balance) and the known concentration in two compartments (Crank, 1975). The major difficulty of the experiment is to set up and to maintain the steady state conditions. Most authors also neglect to take into account the presence of boundary layers on both sides of the sample which change the partial pressure at the surface and distort the determined value of diffusivity.

1.2. Sorption/desorption and drying method

The weight of the sample with a well-defined geometry is measured at regular times to evaluate the moisture uptake (in sorption cases) or the moisture loss (in desorption or drying cases) until the final equilibrium is reached. The diffusivity can be calculated from the changing concentration plotted as a function of time (Crank, 1975). The largest difficulty of this drying procedure is to maintain a constant ambient concentration during the experiment. Samples often shrink, as a consequence of which the moisture diffusivity varies with the moisture content. It is important to notice that this method is again based on the assumption that the external resistance to moisture transfer is negligible, which is not always proven.

1.3. Concentration–distance curve method

The moisture concentration profile within the sample as a function of distance during a one-dimensional unsteady state diffusive process is identified at a certain time. A cylinder of material, containing an initial uniform moisture concentration is place in contact with an environment maintained at lower concentration. The diffusion occurs along the axis of the cylinder (Veraverbeke, Verboven, Scheerlinck, Hoang, & Nicolaï, 2003). After a period of time, the moisture concentration along this axis can be determined by slicing and weighing the samples. An alternative method of high resolution is magnetic resonance imaging; it also allows a non-destructive measurement of moisture profiles (Ruiz-Cabrera, Gou, Foucat, Renou, & Daudin, 2004; Verstreken, Van Hecke, Scheerlinck, De Baerdemaeker, & Nicolaï, 1998).

By the above methods, diffusivity can be identified from experimental data using analytical or numerical solutions of Fick's law of diffusion. The numerical method by finite elements is of great interest in multi-dimensional phenomena but is also a fast and accurate alternative for the other methods for a 1-D case. Numerical methods are not restricted to specific geometries or boundary conditions like analytical ones. In fact there is no standard method for evaluating diffusivity. The choice of the experimental procedure depends on the particular needs of the experiment.

The objective of this work was to estimate the apparent diffusion coefficient of water in different tissues of pear. In the experiment, the driving force was a difference in chemical potential, rather than concentration gradients. The effective diffusivity of cuticle and cortex tissues was estimated with Fick's first and second law, respectively. The latter was solved by means of the finite element method. In article, the effects of picking date, storage period and shelf life temperatures will be investigated.

2. Materials and methods

2.1. Fruits

Conference pears (*Pyrus communis cv.* Conference) were picked at commercial picking date, one week