

Journal of Food Engineering 61 (2004) 373-386

JOURNAL OF FOOD ENGINEERING

www.elsevier.com/locate/jfoodeng

# Modelling shrinkage during convective drying of food materials: a review

L. Mayor, A.M. Sereno \*

Department of Chemical Engineering, Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal Received 6 August 2002; accepted 27 April 2003

### Abstract

Shrinkage of foodstuffs is a common physical phenomenon observed during different dehydration processes. These changes affect the quality of the dehydrated product and should be taken into consideration when predicting moisture and temperature profiles in the dried material. The aim of this work is to give a physical description of the shrinkage mechanism and present a classification of the different models proposed to describe this behaviour in food materials undergoing dehydration. The models were classified in two main groups: empirical and fundamental models. Empirical models are obtained by means of regression analysis of shrinkage data. Fundamental models are based on a physical interpretation of the structure of food materials and try to predict dimensional changes due to volume variation of the different phases in the food system along the drying process. Several models referred to in this work were compared with experimental data on air drying of apple, carrot, potato and squid flesh. Average relative deviations between experimental and predicted values of shrinkage found were in most cases less than 10%. For some materials, models that neglect porosity change tend to show larger deviations.

© 2003 Elsevier Ltd. All rights reserved.

Keywords: Convective drying; Dimensional changes; Mathematical models; Shrinkage; Vegetables

### 1. Introduction

Dehydration of foods is one of the most common processes used to improve food stability, since it decreases considerably the water activity of the material, reduces microbiological activity and minimises physical and chemical changes during its storage.

The present demand of high-quality products in the food market requires dehydrated foods that maintain at a very high level the nutritional and organoleptical properties of the initial fresh product. A thorough understanding of the factors responsible for the decrease in the quality of the product during the dehydration process is thus of major relevance.

One of the most important physical changes that the food suffers during drying is the reduction of its external volume. Loss of water and heating cause stresses in the cellular structure of the food leading to change in shape and decrease in dimension.

\* Corresponding author. Fax: +351-22-508-1449.

E-mail address: sereno@fe.up.pt (A.M. Sereno).

Shrinkage of food materials has a negative consequence on the quality of the dehydrated product. Changes in shape, loss of volume and increased hardness cause in most cases a negative impression in the consumer. There are, on the other hand, some dried products that have had traditionally a shrunken aspect, a requirement for the consumer of raisins, dried plums, peaches or dates.

Surface cracking is another phenomena that may occur during drying. This happens when shrinkage is not uniform during the drying process leading to the formation of unbalanced stresses and failure of the material. Cracking of food materials has been reported by several authors: in gels (starch-agar-MCC) (Gogus & Lamb, 1998), soybean (Mensah, Nelson, Herum, & Richard, 1984), corn (Fortes & Okos, 1980), pasta (Akiyama & Hayakawa, 2000). This cracking phenomenon has been successfully modelled by coupling equations of heat and mass transfer by several authors: Akiyama, Liu, and Hayakawa (1997), Akiyama and Hayakawa (2000), Izumi and Hayakawa (1995), Litchfield and Okos (1988).

<sup>0260-8774/\$ -</sup> see front matter @ 2003 Elsevier Ltd. All rights reserved. doi:10.1016/S0260-8774(03)00144-4

# Nomenclature

A	area, m <sup>2</sup>	ρ	density, $kg m^{-3}$
$a_v$	surface area to volume ratio, $m^{-1}$	X	constituent concentration (kg/kg dry mat-
d	non-sugar dry matter (kg/kg dry matter)		ter)
$egin{array}{c} d \ D_{ m R} \ D_{ m eff} \ E_{ m a} \ k_i \ L \ m \ M \ p_i \ S_{ m b} \end{array}$	non-sugar dry matter (kg/kg dry matter) shrinkage dimension (volume, area, thickness) effective diffusivity, $m^2 s^{-1}$ activation energy, J mol <sup>-1</sup> numerical constants of empirical equations thickness, m mass, kg mass fraction (kg/kg, total mass) parameters of fundamental models (variable) relative volumetric shrinkage (V/V <sub>0</sub> )	Subscr a b ce cr cw e ex f	ter) <i>ripts</i> air bulk cellular critical cell wall material equilibrium excess final
r	radius, m	g	glass transition
R	universal gas constant cal mol <sup><math>-1</math></sup> K <sup><math>-1</math></sup>	j	water soluble components
KH	relative number of the second se	i	component
l T	time, s	0	initial
I V	temperature, $C$	ose	cellulose
V Vn	bed volume $m^3$	op	open pore
Vв X	moisture content dry basis (kg water/kg dry	p	particle
	solid)	R	reduced (current value/initial value)
$X_v$	volume fraction of water (volume of water/	Ro	reduced (current value/ value at $X = 0$ )
U	total volume)	S	solid
Graak	sumbols	sg	solution
R	symuous shrinkage coefficient	st	starch
μ ε	norosity	SL W	water
0	porosity	**	water

Another important consequence of shrinkage is the decrease of the rehydration capability of the dried product. Jayaraman, Das Gupta, and Babu Rao (1990), studying the air drying of cauliflower, reported the inability of the plant tissue to fully rehydrate, and they attributed this fact to the dense and collapsed structure of the dried material, with largely shrunken capillaries. Mcminn and Magee (1997b), in the air drying of potatoes at different process temperatures, reported that when comparing samples with the same moisture content but different degree of shrinkage due to the different drying conditions used, a lower dehydration capacity corresponded to most shrunk samples.

Several authors have tried to relate the effect of collapse and porosity with the kinetics and extension of some chemical reactions in foods undergoing drying and further storage. White and Bell (1999) reported that in a model food system composed by glucose and glycine included in an inner matrix, the elimination of porosity due to structural collapse decreased the glucose loss rate constant, but had a minimal effect on the rate of brown pigment development associated with the Maillard reaction. In model food materials with encapsulated lipids, structural collapse can lead to the releasing of the oil from the matrix, followed by its oxidation in contact with the oxygen of the gas phase of the food system (Labrousse, Roos, & Karel, 1992; Shimada, Roos, & Karel, 1991). Remaining encapsulated lipids are more stable to oxidation (Shimada et al., 1991).

In food systems shrinkage is rarely negligible, and it is advisable to take it into account when predicting moisture content profiles in the material undergoing dehydration. For such purpose different types of models that predict volume change in the material are available and should be used.

Several authors have successively reviewed the process of food dehydration both from an experimental and modelling viewpoint, pinpointing new approaches and methodologies. Some representative examples of such effort are the works of Bruin and Luiben (1980), Chirife (1983), Holdsworth (1971), Jayaraman and Das Gupta (1992), King (1971), Rossen and Hayakawa (1977), Van Ardsel (1963), Waananen, Litchfield, and Okos (1993).

This work will focus rather on physical and mathematical models found in recent literature to explain shrinkage phenomenon, assessing their comparative advantages based on experimental data obtained in drying of apple, carrot, potato and squid flesh.

# 2. Mechanism of shrinkage

Solid and semi-solid food systems are highly heterogeneous materials that may be considered as consisting of a three-dimensional solid network or matrix holding usually large quantities of a liquid phase, in most cases an aqueous solution. Biopolymers are the common structural elements of the solid matrix. In more complex cases a composite structure is formed by the incorporation of additional structural elements (Aguilera, 1992). The particular structure of the material and the mechanical characteristics of its elements at equilibrium, define sample volume and determine its size and shape. When water is removed from the material, a pressure unbalance is produced between the inner of the material and the external pressure, generating contracting stresses that lead to material shrinkage or collapse, changes in shape and occasionally cracking of the product. This is also the reason why drying under vacuum, as in freeze-drying, leads in general to much less shrinkage.

# 2.1. Factors affecting the magnitude of shrinkage

# 2.1.1. Volume of removed water

Shrinkage of food materials increases with the volume of water removed, since the more the water removed the more contraction stresses are originated in the material. In some cases the mechanical equilibrium is reached when shrinkage of the material equals volume



Fig. 1. Ratio of volume of removed water vs. fractional decrease in sample volume for carrot drying. Solid line represents the diagonal.



Fig. 2. Ratio of volume of removed water vs. fractional decrease in sample volume for squid body drying. Solid line represents the diagonal.



Fig. 3. Ratio of volume of removed water vs. fractional decrease in sample volume for potato and sweet potato drying. Solid line represents the diagonal.

of removed water. Figs. 1–4 represent volume of removed water versus volume sample decrease for different food materials. In shrinkage data for carrot drying presented by Krokida and Maroulis (1997) and Lozano, Rotstein, and Urbicain (1983) (Fig. 1), this behaviour is observed during the whole drying process. In other cases, however, the volume of removed water during the final stages of drying is larger than the reduction in sample volume; this was observed during the drying of squid flesh (Rahman & Potluri, 1990; Rahman, Perera, Chen, Driscoll, & Potluri, 1996) (Fig. 2), potato and sweet potato (Lozano et al., 1983; Wang & Brennan, 1995) (Fig. 3), and apple (Krokida & Maroulis, 1997; Lozano, Rotstein, & Urbicain, 1980; Moreira,



Fig. 4. Ratio of volume of removed water vs. fractional decrease in sample volume for apple drying. Solid line represents the diagonal.

Figueiredo, & Sereno, 2000) (Fig. 4). This behaviour can be explained by the decrease in the mobility of the solid matrix of the material at low moisture contents, as described below.

#### 2.1.2. Mobility of the solid matrix

The mobility of the solid matrix is closely related to its physical state; high mobility corresponds to a viscoelastic behaviour typical of a rubbery state while low mobility corresponds to an elastic behaviour typical of a glassy state. Levi and Karel (1995) found that mobility of the solid matrix is a dynamic process with rates that depend on the difference  $(T - T_g)$ , where T is the temperature of the sample undergoing dehydration and  $T_{g}$  is its glass transition temperature, and that Williams-Landel-Ferry (WLF) equation (Williams, Landel, & Ferry, 1955) applies. Similarly, several authors (Achanta, Okos, Cushman, & Kessler, 1997; Del Valle, Cuadros, & Aguilera, 1998; Karathanos, Anglea, & Karel, 1993; Willis, Okos, & Campanella, 1999) have related the extension of shrinkage in air drying with  $(T - T_g)$ . At high moistures, when the material is in the rubbery state, shrinkage almost entirely compensates for moisture loss, and volume of the material decreases linearly with moisture content. At low moisture contents  $T_{\rm g}$  increases, allowing the material to pass from rubbery to glassy state, and the rate and extension of shrinkage decreases significantly. This behaviour may explain deviations from linearity observed by several authors in the relative change of sample volume vs. the relative change of moisture content (Lozano et al., 1983  $(0.1 X/X_0, \text{ garlic, potato, sweet potato});$  Ratti, 1994  $(0.3 X/X_0, \text{ apple, potato})$ , Wang & Brennan, 1995  $(0.1 X/X_0, \text{ potato})$ , Achanta et al., 1997  $(0.3 X/X_0, X_0)$ starch-gluten gel)) observed during the final stage of convective drying. When drying process is in the range of low moisture content where phase transition from rubbery to glassy state is going on, rigidity of the material stops shrinkage and parallel pore formation may happen.

# 2.1.3. Drying rate

If rapid drying rate conditions are used and intense moisture gradients through the material are observed, low moisture content of the external surface may induce a rubber-glass transition and the formation of a porous outer rigid crust or shell that fixes the volume and complicates subsequent shrinkage of the still rubbery inner part of the food. The formation of a shell during drying of gels was verified experimentally by Schrader and Litchfield (1992), by means of magnetic resonance imaging; Wang and Brennan (1995), during drying of potatoes, showed light microscopy evidence of this shell formation or "case hardening" effect. If low drying rate conditions are used, diffusion of water from the inner to the outer zone of the material happens at the same rate than evaporation from the surface, no sharp moisture gradients are formed in the material that shrinks uniformly until the last stages of drying. This behaviour was noticed by Litchfield and Okos (1992) during drying of pasta and by Wang and Brennan (1995) during drying of potato.

The shell formation effect cannot be observed if drying conditions do not allow a phase transition in the outer zone material, even at high drying rates. Willis et al. (1999), during drying of pasta, observed a higher shrinkage when samples were dehydrated at 100 °C and 50% relative humidity than in samples dehydrated at 40 °C at the same relative humidity of air. In the first case drying temperature was greater than glass transition temperature of the pasta, the product remained in the rubbery state and shrank uniformly during the whole drying process. In the second case, the case hardening effect was observed due to a glass transition in the surface of the material, that decreased shrinkage and increased residual stresses in the dried material, which underwent cracking and breakage during storage.

# 2.1.4. Other processing conditions

Several authors have tried to study the influence of different process conditions in volume change of the materials during dehydration. In most cases such analysis has been done studying the effect of each single process condition like temperature (Mcminn & Magee (1997a), with potato), velocity of air (Ratti, 1994; with potato, apple and carrot; Khraisheh, Cooper, & Magee, 1997, with potato) or relative humidity of air (Ratti, 1994 with potato, apple and carrot; Lang & Sokhansanj, 1993 with wheat and canola kernels). Unfortunately the results of these works are often unclear as to the influence of those process conditions on shrinkage. Whereas increase of drying temperature produced less shrinkage in some cases (Del Valle et al., 1998; Mcminn & Magee, 1997a; Wang & Brennan, 1995) in others the influence was not well defined (Ratti, 1994 with potato, apple and carrot). Khraisheh et al. (1997), with potato, and Ratti (1994), with potato, apple and carrot, found that the increase in air velocity produced less shrinkage, which magnitude depended on the kind of material undergoing dehydration. Lang and Sokhansanj (1993), with wheat and canola kernels, found a slight influence of the relative humidity of air on shrinkage that appears to increase with the relative humidity of air, whereas Ratti (1994), still with potato, apple and carrot, found no appreciable influence of air humidity in the range conditions studied. As suggested before, it is believed that it is the combined effect of process conditions when facilitating the formation of a crust or shell in the external surface of the product during the initial stage of the drying process that determines the type and extent of shrinkage.

#### 3. Modelling shrinkage during convective drying

Drying of foods is a complex process involving simultaneous mass and energy transport in a system that suffers different changes in its chemical composition, structure and physical properties. For some time shrinkage was considered negligible in drying modelling, thus making drying models easier to be solved. However, in food systems shrinkage is rarely negligible. Balaban (1989) used two mathematical models to describe simultaneous heat and mass transfer on foods, with and without the assumption of volume change, showing both models significant differences in predicted moisture and temperature gradients, and average moisture contents and temperatures. Experimental results for drying of fish muscle were compared with predicted results of both models. Model with shrinkage fitted better experimental data than model without shrinkage. Similarly, Park (1998), studying the dehydration of shark muscle, used again two models considering and neglecting shrinkage; the results led to significant differences in the values of  $D_{\rm eff}$  and its temperature dependence, expressed in terms of an Arrhenius-type equation and an activation energy. Simal, Rosselló, Berna, and Mulet (1998) found also different values of  $D_{\rm eff}$  calculated using a Fickian model with and without shrinkage; predicted drying curves were more accurate when sample shrinkage was considered. Above results suggest that modelling taking shrinkage into account lead to better predictions of values of  $D_{\rm eff}$ , moisture content profiles and average values of moisture content during the process.

Two substantial different approaches have been taken in order to model shrinkage during drying of food materials. The first one consists on an empirical fitting of experimental shrinkage data as a function of moisture content. The second approach is more fundamental and based on a physical interpretation of the food system and tries to predict geometrical changes based on conservation laws of mass and volume. In both cases linear and non-linear models result to describe shrinkage behaviour versus moisture content.

#### 3.1. Definitions

Some concepts required to describe the different equations that will be presented in the next section must be introduced. These definitions, most of them initially collected by Rahman et al. (1996) and Zogzas, Maroulis, and Marinos-Kouris (1994), are based on the assumption that the total mass of moist material consists in dry solids, water and air.

Shrinkage,  $D_R(S_b)$ : Represents a relative or reduced dimensional change of volume, area or thickness; volume shrinkage is often represented by  $S_b = V/V_0$ .

*Bulk density*,  $\rho_b$ : Bulk density of the material is the ratio between the current weight of the sample and its overall volume:

$$\rho_{\rm b} = \frac{m_{\rm s} + m_{\rm w}}{V_{\rm s} + V_{\rm w} + V_{\rm a}} \tag{1}$$

where  $m_s$  and  $m_w$  are the masses of dry solids and water, respectively; and  $V_s$ ,  $V_w$  and  $V_a$  are the volumes of dry solids, water and air pores respectively in a material sample.

*Particle density*,  $\rho_p$ : Particle density is the ratio between the current total mass of the sample and its overall volume excluding the air pores:

$$\rho_{\rm p} = \frac{m_{\rm s} + m_{\rm w}}{V_{\rm s} + V_{\rm w}} \tag{2}$$

Dry solids density,  $\rho_s$ : Dry solids density is the ratio between the mass of the solids in the sample and the volume occupied by those solids:

$$\rho_{\rm s} = \frac{m_{\rm s}}{V_{\rm s}} \tag{3}$$

Equilibrium density,  $\rho_e$ : Equilibrium density is the ratio between the mass of the sample after equilibration with environmental air at drying conditions and its overall volume in such conditions,  $V_e = (V_s + V_w + V_a)_{equilibrium}$ .

$$\rho_{\rm e} = \frac{m_{\rm e}}{V_{\rm e}} \tag{4}$$

*True density of pure components*,  $\rho_i$ : The density of a pure component substance *i* of any complex material is calculated from its mass and volume:

$$\rho_i = \frac{m_i}{V_i}$$

Table 1	l		
Linear	empirical	models	

Type of model	Geometry	Reduced dimension	Material	Reference
$D_{\rm R} = k_1 X + k_2$	Cylinder	Volume	Apple	Lozano et al. (1980)
	Sphere	Radius	Soybean	Misra and Young (1980)
	Ellipsoid	x, y, z co-ordinates	Apricot	Vagenas and Marinos-Kouris (1991)
	Cylinder	Volume	Carrot	Ratti (1994)
	Cylinder	Volume	Amylose starch gel	Izumi and Hayakawa (1995)
	Sphere	Radius $(r_2 \ge r \ge r_1)$	Apricot	Mahmutoglu, Pala, and Unal (1995)
	Slab	Thickness, width, length	Potato	Wang and Brennan (1995)
	Slab	Thickness	Apple	Kaminski, Szarycz, and Janowicz (1996)
	Sphere	Volume	Grape	Simal, Mulet, Catalá, Cañellas, and Rosselló (1996)
	Cylinder and slab	Volume $(0.2 \le X/X_0 \le 1)$	Potato	Khraisheh et al. (1997)
	Cylinder	Volume, radial, axial	Green bean	Rosselló, Simal, SanJuan, and Mulet (1997)
	Sphere	Volume	Grape	Azzouz, Jomaa, and Belghith (1998)
	Sphere	Volume	Potato	Mclaughlin and Magee (1998)
	Slab	Thickness, width, length	Fish muscle (shark)	Park (1998)
	Cylinder	Volume	Broccoli stem	Simal et al. (1998)
	Cylinder	Volume	Apple	Moreira et al. (2000)
	Cube, cylinder	Volume	Potato	Mulet, Garcia-Reverter, Bon, and Berna (2000)
	Parallelepiped cylinder	Radius	Banana	Queiroz and Nebra (2001)
	Cylinder	Volume	Carrot	Hatamipour and Mowla (in press)
	Sphere	Volume	Cherry	Ochoa, Kesseler, Pirone, Márquez, and De Michelis (2002)
$D_{\rm R} = k_3 X_v + k_4$	Slab	Thickness, width, length	Fish muscle (ocean perch)	Balaban and Pigott (1986)
$\begin{cases} k_5 & \text{for } X < X_c \\ k_6 + k_7 (X - X_c) & \text{for } X \ge X_c \end{cases}$	Cylinder	Volume	Amylose gel	Tsukada, Sakai, and Hayakawa (1991)
$D_{\rm R} = k_8 + k_9 X$ for $X < X_{\rm c}$	Cylinder	Volume	Apple, potato	Ratti (1994)
$D_{\rm R} = k_{10} + k_{11} X  \text{for } X \ge X_{\rm c}$	Cylinder	Volume	Amylose gel	Akiyama et al. (1997)
$D_{\rm Ro} = 1 + \beta X$	Cube	Volume	Apple, carrot, potato	Zogzas et al. (1994)
	Slab	Thickness	Gelatine gel	Bonazzi, Ripoche, and Michon (1997)
	Cylinder	Volume	Apple, carrot, potato, banana	Krokida and Maroulis (1997)
	Slab	Thickness	Carrot	Bouaziz and Belghith (1998)
$D_{\mathrm{Ro}} = 1 + \left(k_{12} \exp\left(\frac{-E_{\mathrm{a}}}{RT}\right)\right) X$	Sphere	Volume	Grape	Gabas, Menegalli, and Telis-Romero (1999)
$\Delta D_{\rm R} = k_{13} + (k_{14} + k_{15} {\rm RH} + k_{16} T) \Delta X$	Sphere	Bed volume	Wheat and canola	Lang and Sokhansanj (1993)
$D_{\rm R} = (k_{17}T + k_{18}) + (k_{19}T + k_{20})X$	Cylinder	Volume	Potato	Mcminn and Magee (1997a)

*Porosity*,  $\varepsilon$ : The porosity is the ratio between the volume of air present in the sample and the overall volume

$$\varepsilon = \frac{V_{\rm a}}{V_{\rm s} + V_{\rm w} + V_{\rm a}}\tag{5}$$

expressed as a function of bulk and particle density, Eq. (5) takes the form:

$$\varepsilon = 1 - \frac{\rho_{\rm b}}{\rho_{\rm p}} \tag{6}$$

*Excess volume fraction*,  $\varepsilon_{ex}$ : The excess volume fraction is the ratio between the excess volume, defined as the change in volume that results from the mixture of the pure components at a given temperature and pressure, and the overall volume:

$$\varepsilon_{\rm ex} = \frac{V_{\rm ex}}{V_{\rm s} + V_{\rm w} + V_{\rm a}} \tag{7}$$

Table 2

Non-linear empirical models

# 3.2. Mathematical models for shrinkage

#### 3.2.1. Empirical models

The simplest way to model shrinkage during dehydration is to obtain an empirical correlation between shrinkage and moisture content, including occasionally process conditions like temperature and humidity of air. Several examples of those models are presented in Tables 1 and 2.

Linear models (Table 1) are adequate to describe materials and process conditions leading to negligible porosity development during the drying process, or to an uniform development of porosity, corresponding to a linear decrease of volume in the whole range of humidity. If development of porosity increases sharply during the final stage of drying, linearity is lost and the behaviour is best described by exponential models (Mulet et al., 1997; this work, Table 2), two consecutive linear approximations, with a critical moisture content ( $X_c$ ) defined at their intersection (Akiyama et al., 1997;

Geometry	Reduced dimension	Material	Reference
Cylinder, slab (garlic)	Volume	Carrot, garlic, pear, potato, sweet potato	Lozano et al. (1983)
Cylinder	Surface area to volume ratio	Apple, carrot, potato	Ratti (1994)
Sphere	Surface area to volume ratio	Potato	Mclaughlin and Magee (1998)
Sphere	Surface area to volume ratio	Cherrie	Ochoa et al. (2002)
Cylinder	Bed volume	Apple, carrot, potato	Ratti (1994)
Slab	Surface area	Potato and squash	Rovedo, Suárez, and Viollaz (1997)
Slab	Thickness	Apple	Kaminski et al. (1996)
Hemisphere, cylinder	Diameter, length	Cauliflower	Mulet, Tarrazo, García- Reverter, and Berna (1997)
Slab	Thickness	Garlic	Vázquez, Chenlo, Moreira, and Costoyas (1999)
Cylinder, slab	Volume	Apple, carrot, potato, squid	Quadratic (this work)
Cylinder, slab	Volume	Apple, carrot, potato, squid	Exponential (this work)
	Geometry Cylinder, slab (garlic) Cylinder Sphere Sphere Cylinder Slab Slab Hemisphere, cylinder Slab Cylinder, slab Cylinder, slab	GeometryReduced dimensionCylinder, slab (garlic)VolumeCylinderSurface area to volume ratioSphereSurface area to volume ratioSphereSurface area to volume ratioSphereSurface area to volume ratioSphereSurface area to volume ratioSlabSurface areaSlabSurface areaSlabThicknessHemisphere, cylinderDiameter, lengthSlabThicknessCylinder, slabVolumeCylinder, slabVolume	GeometryReduced dimensionMaterialCylinder, slab (garlic)VolumeCarrot, garlic, pear, potato, sweet potatoCylinderSurface area to volume ratioApple, carrot, potatoSphereSurface area to volume ratioPotatoSphereSurface area to volume ratioCherrieSphereSurface area to volume ratioCherrieSphereSurface area to volume ratioCherrieSlabSurface areaPotato and squashSlabSurface areaPotato and squashSlabThicknessAppleHemisphere, cylinderDiameter, lengthCauliflowerSlabThicknessGarlicCylinder, slabVolumeApple, carrot, potato, squidCylinder, slabVolumeApple, carrot, potato, squid

Ratti, 1994), or a quadratic model as used in the present work (see Table 2).

These models usually present a good fit to experimental data, but their use is limited because of their dependence on the drying conditions and on the material characteristics. They require extensive experimental testing and should not be extrapolated. Nevertheless they have been used in more complex drying models with reasonable success (Akiyama & Hayakawa, 2000; Itaya, Kobayashi, & Hayakawa, 1995; Simal et al., 1996).

#### 3.2.2. Fundamental models

These models, based on mass balances, density and porosity definitions, assume in most cases additivity of the volumes of the different phases in the system. An exception to this volume additivity is the model proposed by Rahman et al. (1996) accounting for the interaction between the phases of the material by means of an excess volume due to the interaction of the component phases. This excess volume may be positive or negative depending on the physicochemical nature of the process.

Tables 3–5 present some of such models. They have been classified in three groups: models which show a linear shrinkage behaviour throughout the whole drying process (Table 3); models which include deviations of this linear behaviour (Table 4) and models which include explicitly variations of the porosity through the drying process (Table 5). In the case of porous materials, the model proposed by Perez and Calvelo (1984) can be improved by taking into account the initial porosity of the material:

$$\frac{V}{V_0} = \frac{1}{(1-\varepsilon)} \left[ 1 + \frac{\rho_0(X-X_0)}{\rho_w(1+X_0)} - \varepsilon_0 \right]$$
(8)

Fundamental models allow the prediction of moisture content and/or change in volume to be obtained without complicated mathematical calculations. Furthermore, it is not usually necessary to obtain experimental shrinkage values at every process conditions, as in the case of empirical models.

# 3.3. Assessment of the quality of different shrinkage models fitted to experimental data

Based on comprehensive sets of experimental data on air drying of apple (Moreira et al., 2000), carrot (Krokida & Maroulis, 1997), potato (Lozano et al., 1983) and squid (Rahman et al., 1996), it was possible to compare the quality of several shrinkage models described in the literature and to draw some conclusions on their relative merits. Figs. 5–8 for apple drying and Figs. 9–12 for

Equations	Geometry	Reduced dimension	Material	Reference
$\frac{V}{V_0} = \left(\frac{X+0.8}{X_0+0.8}\right); \frac{A}{A_0} = \left(\frac{V}{V_0}\right)^{2/3}$			Vegetables	Kilpatrick, Lowe, and Van Ardsel (1955)
$\frac{V}{V_0} = p_3 + p_4 \frac{X}{X_0}; p_3 = \frac{1}{X_0(\rho_s/\rho_w) + 1}$		Volume	Sugar beet root	Vacarezza (1975)
$p_4 = rac{X_0( ho_s/ ho_w)}{X_0( ho_s/ ho_w+1)}$				
Uniform drying model:	Cube	Area	Carrot, potato,	Suzuki, Kubota,
$\frac{A}{A_0} = \left(\frac{V}{V_0}\right)^{2/3}$ Model A:			sweet potato, radish	Hasegawa, and Hosaka (1976)
$\frac{V}{V_0} = \frac{X + p_5}{X_0 + p_5}; p_5 = X_e \left(\frac{1}{\rho_e} - 1\right) + \frac{1}{\rho_e}$				
Model B:				
$rac{V}{V_0} = p_6 X + p_7;  p_6 = rac{ ho_0}{X_0 + 1};  p_7 = 1 + p_6 -  ho_0$				
Core drying model:	Cube	Area	Carrot, potato,	Suzuki et al. (1976)
$\frac{V}{V_0} = p_8 X + 1; \ p_8 = \frac{1 - p_9}{X_0 - X_e}$			sweet potato, radish	
$p_9 = \frac{(X_e + 1)\rho_0}{(X_0 + 1)\rho_e}, \frac{A}{A_0} = \left(\frac{V}{V_0}\right)^{2/3}$				

Table 3

Linear fundamental models

Table 4	
Non-linear fundamenta	al models

Equations	Geometry	Reduced dimension	Material	Reference
Semi-core drying model: $\frac{V}{V} = p_{10}X + p_{11}; \frac{A}{A} = \left(\frac{V}{V}\right)^{2/3}$	Cube	Area	Carrot, potato, sweet potato, radish	Suzuki et al. (1976)
$p_{10} = \frac{A_0}{X_0 - X_e - p_{12}(p_9X_0 - X_e + p_9 - 1)}$				
$p_{11} = \frac{p_0 X_0 - X_e - p_{12}(p_0 X_0 - X_e + p_0 - 1)}{X_0 - X_e - p_{12}(p_0 X_0 - X_e + p_9 - 1)}$				
$p_{12} = \frac{\rho_{\rm e} - (1 - X)\rho_{\rm e}}{\rho_0}$				
$S_{\rm cc} = \left[ \frac{\left( X + \frac{\sum_j \chi_j}{d + \sum_j \chi_j} \right) + \frac{d}{d + \sum_j \chi_j} \frac{\rho_{\rm sn}}{\rho_{\rm ose}}}{X_0 + \frac{\sum_j \chi_j}{d + \sum_j \chi_j} + \frac{d}{d + \sum_j \chi_j} \frac{\rho_{\rm sn,0}}{\rho_{\rm sn}}} \right] \frac{\rho_{\rm sn,0}}{\rho_{\rm sn}}$	Cylinder	Volume	Apple	Lozano et al. (1980)
$D_{\rm R} = p_3 + p_4 \frac{X}{X_0} + 0.26 p_2 \left(1 - \frac{X}{X_0}\right)^3$	Cylinder	Volume	Cassava root	Sgroppo, Gabitto, Aguerre, Fusco, and Avanza (1990)

Table 5

Fundamental models including porosity

Equations	Geometry	Reduced dimension	Material	Reference
Model A (inclusion of initial porosity) $\begin{bmatrix} X \\ -X \end{bmatrix}$	Cylinder, slab (garlic)	Volume	Carrot, garlic, pear, potato,	Lozano et al. (1983)
$D_{\mathrm{R}} = \left[ p_{13} \overline{X_0} + p_{14}(X) \right] p_{15}$			sweet potato	
$p_{13} = \left(1 + \frac{\chi_{\rm sg}}{X_0} + \frac{\rho_{\rm sn,0}}{X_0} p_{16}\right)$				
$p_{14} = \frac{(\chi_{\rm sg} + \rho_{\rm sn}(X)p_{16})p_{13}}{X_0}$				
$p_{15} = \frac{1 - \varepsilon(X_0)\rho_{\mathrm{sn}}(X_0)}{1 - \varepsilon(X)\rho_{\mathrm{sn}}(X)}; p_{16} = \frac{\chi_{\mathrm{cw}}}{\rho_{\mathrm{cw}}} + \frac{\chi_{\mathrm{st}}}{\rho_{\mathrm{st}}}$				
Model $B$ (without inclusion of initial porosity)	Cylinder,	Volume	Carrot, garlic,	Lozano et al. (1983)
$D_{\mathrm{R}} = rac{1}{(1-arepsilon)} rac{\left(p_{16}+rac{\chi_{\mathrm{sg}}}{ ho_{\mathrm{sg}}}+rac{\chi}{ ho_{\mathrm{sn}}} ight) ho_{0}}{X_{0}+1}$	siab (gariic)		sweet potato	
$D_{\mathrm{R}} = rac{1}{(1-arepsilon)} \left[ 1 + rac{ ho_0(X-X_0)}{ ho_w(1+X_0)}  ight]$	Slab	Volume	Beef meat	Perez and Calvelo (1984)
$D_{\mathrm{R}} = rac{ ho_0}{ ho} \left[ rac{1+X}{1+X_0}  ight]  ho = rac{(1-arepsilon_{\mathrm{ex}}-arepsilon)}{\sum_{i=1}^m rac{M_i}{( ho_m)_i}}$	Slab	Volume	Squid	Rahman et al. (1996)
$D_{\rm R} = \frac{1}{(1-\varepsilon)} \left[ 1 + \frac{\rho_0 (X - X_0)}{\rho_w (1 + X_0)} - \varepsilon_0 \right]$	Cylinder	Volume	Apple, potato, carrot, squid	Modified Perez and Calvelo (this work)

carrot drying show experimental shrinkage data and values predicted with selected models from Tables 1–5. Table 6 shows the average percent relative deviation between the assessed models and the experimental values of volumetric shrinkage for the four products.

Empirical models showed an acceptable fit to experimental data for all the materials tested, being the exponential model the one leading to larger deviation between experimental and predicted values. The model with two consecutive linear approximations



Fig. 5. Experimental shrinkage data for apple drying (Moreira et al., 2000) and prediction by empirical models.



Fig. 6. Experimental shrinkage data for apple drying (Moreira et al., 2000) and prediction by linear fundamental models.



Fig. 7. Experimental shrinkage data for apple drying (Moreira et al., 2000) and prediction by non-linear fundamental models.



Fig. 8. Experimental shrinkage data for apple drying (Moreira et al., 2000) and prediction by fundamental models including porosity.



Fig. 9. Experimental shrinkage data for carrot drying (Krokida & Maroulis, 1997) and prediction by empirical models.



Fig. 10. Experimental shrinkage data for carrot drying (Krokida & Maroulis, 1997) and prediction by linear fundamental models.



Fig. 11. Experimental shrinkage data for carrot drying (Krokida & Maroulis, 1997) and prediction by non-linear fundamental models.



Fig. 12. Experimental shrinkage data for carrot drying (Krokida & Maroulis, 1997) and prediction by fundamental models including porosity.

Table 6

Average relative deviation (%) between experimental data and predicted values of volumetric shrinkage for different food materials

Model	Material					
Empirical	Apple <sup>(1)</sup>	Carrot <sup>(2)</sup>	Potato <sup>(3)</sup>	Squid <sup>(4)</sup>		
Linear	7.0	1.2	2.9	1.7		
Quadratic (this work)	7.0	1.0	2.5	1.3		
Exponential (this work)	8.1	19	8.6	11.3		
Lozano et al. (1983)	8.0	56	12	7.9		
Ratti (1994)	6.8	-	1.5	1.1		
Linear fundamental						
Kilpatrick et al. (1955)	33	6.6	4.1	9.8		
Vacarezza (1975)	37	2.4	5.5	2.8		
Suzuki et al. (1976), core model	7.9	4.0	10	2.1		
Suzuki et al. (1976), uniform model (A)	8.6	3.8	6.7	2.2		
Suzuki et al. (1976), uniform model (B)	13	1.6	7.1	3.4		
Non-linear fundamental						
Suzuki et al. (1976), semi-core model	8.9	20	7.7	6.7		
Sgroppo et al. (1990)	32	6.1	4.8	8.0		
Explicit inclusion of porosity						
Lozano et al. (1983) (A)	22 $(X/X_0 > 0.1)$	11	9.6	9.8		
Lozano et al. (1983) (B)	10	3.2	7.9	2.8		
Perez and Calvelo (1984)	40 $(X/X_0 > 0.1)$	3.0	2.7	2.1		
Rahman et al. (1996)	7.2	7.6	5.5	2.2		
Modified Perez and Calvelo	7.7	1.5	19	3.4		

Experimental data: (1) Moreira et al. (2000); (2) Krokida and Maroulis (1997); (3) Lozano et al. (1983); (4) Rahman et al. (1996).

proposed by Ratti (1994), when applicable (apple, carrot and potato), presented the best fit among empirical models.

models.With some exceptions, fundamental models presenteddeviations similar to those observed with empirical ones.This is a remarkable result suggesting that a good ac-

were found, whether these were due more to the quality of the data than the quality of the model.

This is a remarkable result suggesting that a good accuracy can be reached with such fundamental models. It was not possible to conclude, when larger deviations Shrinkage of foods during drying has an impact on product quality of the dried product. If the extension of shrinkage during the drying process is controlled, quality of the dehydrated product may be improved. For this purpose, a good knowledge of shrinkage mechanism and the influence of process variables on shrinkage are needed. Furthermore, this phenomenon affects the predictions of moisture and temperature profiles obtained by drying models and should be taken into account in the mathematical simulation of the drying process.

As far as shrinkage modelling is concerned, while empirical models are convenient, easy to use and provide a good fit when experimental shrinkage data are known for existing process conditions, fundamental models may be used as well to predict shrinkage.

When porosity formation occurs during the drying process, it should be included in the model to take into account that phenomenon. This can be done either by the inclusion of an equilibrium density or through the ratio of air volume in the sample to its total bulk volume. This porosity formation can change with process conditions, and its inclusion in the model allows taking into account the influence of process conditions on shrinkage.

In general, inclusion of porosity is not very useful to predict bulk shrinkage, since particle and bulk density values must be known to obtain porosity data. However it can be very useful to estimate the porosity of the material if shrinkage values are known.

Among the models that include porosity explicitly, Perez and Calvelo models do not need compositional data of the solid phase to calculate shrinkage. The modification proposed in this work for Perez and Calvelo's model not only improves the physical representation of the food system but also presents a better fit to experimental data than the original model proposed by the authors.

# Acknowledgements

The authors acknowledge the support from EU project TMR-FMRX-CT96-0082 QUID. The author Luis Mayor acknowledges SFRH/BD/3414/2000 PhD grant to Fundação para a Ciência e a Tecnologia, Portugal.

#### References

- Achanta, S., Okos, M. R., Cushman, J. H., & Kessler, D. P. (1997). Moisture transport in shrinking gels during saturated drying. *AIChE Journal*, 43(8), 2112–2122.
- Aguilera, J. M. (1992). Generation of engineered structures in gels. In H. G. Schwartzberg, & R. W. Hartel (Eds.), *Physical chemistry of foods* (pp. 391–393). New York: Marcel Dekker Inc.

- Akiyama, T., Liu, H., & Hayakawa, K. (1997). Hygrostress-multicrack formation and propagation in cylindrical viscoelastic food undergoing heat and moisture transfer processes. *International Journal of Heat and Mass Transfer*, 40(7), 1601–1609.
- Akiyama, T., & Hayakawa, K. (2000). Heat and moisture transfer and hygrophysical changes in elastoplastic hollow cylinder-food during drying. *Journal of Food Science*, 65(2), 315–323.
- Azzouz, S., Jomaa, W., & Belghith, A. (1998). Drying kinetic equation of single layer of grapes. In *Proceedings of the 11th international* symposium (pp. 988–997), vol. B.
- Balaban, M., & Pigott, G. M. (1986). Shrinkage in fish muscle during drying. Journal of Food Science, 51(2), 510–511.
- Balaban, M. (1989). Effect of volume change in foods on the temperature and moisture content predictions of simultaneous heat and moisture transfer models. *Journal of Food Process Engineering*, 12, 67–88.
- Bonazzi, C., Ripoche, A., & Michon, C. (1997). Moisture diffusion in gelatin slabs by modeling drying kinetics. *Drying Technology*, 15(6/ 8), 2045–2059.
- Bouaziz, N., & Belghith, A. (1998). Heat and mass transfer during the convective drying: from the sample behaviour to the dryer project. In *Proceedings of the 11th international symposium* (pp. 118–125), vol. A.
- Bruin, S., & Luiben, K. C. A. M. (1980). Drying of food materials: A review of recent developments. In A. S. Mujumdar (Ed.), *Advances in drying* (vol. I, pp. 155–215). New York: Hemisphere Publishing Corp.
- Chirife, J. (1983). Fundamentals of the drying mechanism during air dehydration of foods. In A. S. Mujumdar (Ed.), *Advances in drying* (vol. 2, pp. 73–102). New York: Hemisphere Publishing Corp.
- Del Valle, J. M., Cuadros, T. R. M., & Aguilera, J. M. (1998). Glass transitions and shrinkage during drying and storage of osmosed apple pieces. *Food Research International*, 31(3), 191–204.
- Fortes, M., & Okos, M. R. (1980). Changes in physical properties of corn during drying. *Transactions of the ASAE*, 1004–1008.
- Gabas, A. L., Menegalli, F. C., & Telis-Romero, J. (1999). Effect of chemical pretreatment on the physical properties of dehydrated grapes. *Drying Technology*, 17(6), 1215–1226.
- Gogus, F., & Lamb, J. (1998). Choice of model gel systems for the food dehydration studies. *Drying Technology*, 16(1/2), 297–309.
- Hatamipour, M. S., & Mowla, D. (2002). Shrinkage of carrots during drying in an inert medium fluidized bed. *Journal of Food Engineering*, 55(3), 247–252.
- Holdsworth, S. D. (1971). Dehydration of food products. A review. Journal of Food Technology, 6(4), 331-370.
- Itaya, Y., Kobayashi, T., & Hayakawa, K.-I. (1995). Three-dimensional heat and moisture transfer with viscoelastic strain–stress formation in composite food during drying. *International Journal of Heat and Mass Transfer*, 38(7), 1173–1185.
- Izumi, M., & Hayakawa, K. (1995). Heat and moisture transfer and hygrostress crack formation and propagation in cylindrical, elastoplastic food. *International Journal of Heat and Mass Transfer*, 38(6), 1033–1041.
- Jayaraman, K. S., & Das Gupta, D. K. (1992). Dehydration of fruits and vegetables—recent developments in principles and techniques. *Drying Technology*, 10(1), 1–50.
- Jayaraman, K. S., Das Gupta, D. K., & Babu Rao, N. (1990). Effect of pretreatment with salt and sucrose on the quality and stability of dehydrated cauliflower. *International Journal of Food Science and Technology*, 25, 47–60.
- Kaminski, E., Szarycz, M., & Janowicz, L. (1996). The kinetics of drying sliced apples in the conditions of natural convection. In Proc. 7th Seminar on Properties of water in foods (pp. 24–34). Warsaw Agricultural University, Poland.
- Karathanos, V., Anglea, S., & Karel, M. (1993). Collapse of structure during drying of celery. *Drying Technology*, 11(5), 1005–1023.

- Khraisheh, M. A. M., Cooper, T. J. R., & Magee, T. R. A. (1997). Shrinkage characteristics of potatoes dehydrated under combined microwave and convective air conditions. *Drying Technology*, 15(3/ 4), 1003–1022.
- Kilpatrick, P. W., Lowe, E., & Van Ardsel, W. B. (1955). Tunnel dehydrators for fruit and vegetables. In E. M. Mrak, & G. F. Stewart (Eds.), *Advances in food research* (vol. 6, pp. 313–372). New York: Academic Press.
- King, C. J. (1971). Freeze-drying of foods. Cleveland, OH: CRC Press, The Chemical Rubber Co.
- Krokida, M. K., & Maroulis, Z. B. (1997). Effect of drying method on shrinkage and porosity. *Drying Technology*, 15(10), 2441– 2458.
- Labrousse, S., Roos, Y., & Karel, M. (1992). Collapse and crystallization in amorphous matrices with encapsulated compounds. *Science des Aliments*, 12, 757–769.
- Lang, W., & Sokhansanj, S. (1993). Bulk volume shrinkage during drying of wheat and canola. *Journal of Food Process Engineering*, 16, 305–314.
- Levi, G., & Karel, M. (1995). Volumetric shrinkage (collapse) in freeze-dried carbohydrates above their glass transition temperature. *Food Research International*, 28(2), 145–151.
- Litchfield, J. B., & Okos, M. R. (1988). Prediction of corn kernel stress and breakage induced by drying, tempering, and cooling. *Trans*actions of the ASAE, 31, 585–594.
- Litchfield, J. B., & Okos, M. R. (1992). Moisture diffusivity in pasta during drying. *Journal of Food Engineering*, 17, 117–142.
- Lozano, J. E., Rotstein, E., & Urbicain, M. J. (1980). Total porosity and open-pore porosity in the drying of fruits. *Journal of Food Science*, 45, 1403–1407.
- Lozano, J. E., Rotstein, E., & Urbicain, M. J. (1983). Shrinkage, porosity and bulk density of foodstuffs at changing moisture contents. *Journal of Food Science*, 48, 1497–1502, 1553.
- Mahmutoglu, T., Pala, M., & Unal, M. (1995). Mathematical modelling of moisture, volume and temperature changes during drying of pretreated apricots. *Journal of Food Processing and Preservation*, 19, 467–490.
- Mclaughlin, C. P., & Magee, T. R. A. (1998). The effect of shrinkage during drying of potato spheres and the effect of drying temperature on vitamin C retention. *Transactions of the IChemE*, 76 (C)(September), 138–142.
- Mcminn, W. A. M., & Magee, T. R. A. (1997a). Physical characteristics of dehydrated potatoes—Part I. *Journal of Food Engineering*, 33, 37–48.
- Mcminn, W. A. M., & Magee, T. R. A. (1997b). Physical characteristics of dehydrated potatoes—Part II. *Journal of Food Engineering*, 33, 49–55.
- Mensah, J. K., Nelson, G. L., Herum, F. L., & Richard, T. G. (1984). Mechanical properties related to soybean seedcoat cracking during drying. *Transactions of the ASAE*, 27, 550.
- Misra, R. N., & Young, J. H. (1980). Numerical solution for simultaneous moisture diffusion and shrinkage during soybean drying. *Transactions of the ASAE*, 1277–1282.
- Moreira, R., Figueiredo, A., & Sereno, A. (2000). Shrinkage of apple disks during drying by warm air convection and freeze drying. *Drying Technology*, 18(1&2), 279–294.
- Mulet, A., Tarrazo, J., García-Reverter, J., & Berna, A. (1997). Shrinkage of cauliflower florets and stems during drying. In R. Jowitt (Ed.), *Engineering and food at ICEF* 7 (pp. 97–100). Sheffield, UK: Sheffield Academic Press.
- Mulet, A., Garcia-Reverter, J., Bon, J., & Berna, A. (2000). Effect of shape on potato and cauliflower shrinkage during drying. *Drying Technology*, 18(6), 1201–1219.
- Ochoa, M. R., Kesseler, A. G., Pirone, B. N., Márquez, C. A., & De Michelis, A. (2002). Volume and area shrinkage of whole sour cherry fruits (*Prunus Cerasus*) during dehydration. *Drying Technology*, 20(1), 147–156.

- Park, K. J. (1998). Diffusional model with and without shrinkage during salted fish muscle drying. *Drying Technology*, 16(3–5), 889– 905.
- Perez, M. G. R., & Calvelo, A. (1984). Modeling the thermal conductivity of cooked meat. *Journal of Food Science*, 49, 152– 156.
- Queiroz, M. R., & Nebra, S. A. (2001). Theoretical and experimental analysis of the drying kinetics of bananas. *Journal of Food Engineering*, 47, 127–132.
- Ratti, C. (1994). Shrinkage during drying of foodstuffs. Journal of Food Engineering, 23(1), 91–105.
- Rahman, M. S., & Potluri, P. L. (1990). Shrinkage and density of squid flesh during air drying. *Journal of Food Engineering*, 12, 133– 143.
- Rahman, M. S., Perera, C. O., Chen, X. D., Driscoll, R. H., & Potluri, P. L. (1996). Density, shrinkage and porosity of Calamari Mantle Meat during air drying in a cabinet dryer as a function of water content. *Journal of Food Engineering*, 30, 135–145.
- Rosselló, C., Simal, S., SanJuan, N., & Mulet, A. (1997). Nonisotropic mass transfer model for green bean drying. *Journal of Agricultural* and Food Chemistry, 45, 337–342.
- Rossen, J. L., & Hayakawa, K. (1977). Simultaneous heat and moisture transfer in dehydrated food: A review of theoretical models. *AIChE Symposium Series*, 73(163), 71–81.
- Rovedo, C. O., Suárez, C., & Viollaz, P. E. (1997). Kinetics of forced convective air drying of potato and squash slabs. *Food Science and Technology International*, 3, 251–261.
- Schrader, G. W., & Litchfield, J. B. (1992). Moisture profiles in a model food gel during drying: measurement using magnetic resonance imaging and evaluation of the Fickian model. *Drying Technology*, 10(2), 295–332.
- Sgroppo, S., Gabitto, J. F., Aguerre, R. J., Fusco, A. J. V., & Avanza, J. R. (1990). Transferencia de masa en sólidos con cambio de volumen. Aplicación al secado de mandioca. *Revista Científica de la* Universidad del Nordeste de la Repúacute blica Argentina (FAC-ENA). Serie: Ciencias exactas 8, 131–146.
- Shimada, Y., Roos, Y., & Karel, M. (1991). Oxidation of methyl linoleate encapsulated in amorphous lactose based food model. *Journal of Agricultural and Food Chemistry*, 39, 637–641.
- Simal, S., Mulet, A., Catalá, P. J., Cañellas, J., & Rosselló, C. (1996). Moving boundary model for simulating moisture movement in grapes. *Journal of Food Science*, 61(1), 157–160.
- Simal, S., Rosselló, C., Berna, A., & Mulet, A. (1998). Drying of shrinking cylinder-shaped bodies. *Journal of Food Engineering*, 37, 423–435.
- Suzuki, K., Kubota, K., Hasegawa, T., & Hosaka, H. (1976). Shrinkage in dehydration of root vegetables. *Journal of Food Science*, 41, 1189–1193.
- Tsukada, T., Sakai, N., & Hayakawa, K. (1991). Computerized model for strain–stress analysis of food undergoing simultaneous heat and mass transfer. *Journal of Food Science*, 56(5), 1438–1445.
- Vacarezza, L. (1975). Cinética y mecanismo de transporte de agua durante la deshidratación de la remolacha azucarera. Ph.D. Thesis. Universidad de Buenos Aires.
- Vagenas, G. K., & Marinos-Kouris, D. (1991). Drying kinetics of apricots. Drying Technology, 9(3), 735–752.
- Van Ardsel, W. E. (1963). Food dehydration. Volume I—principles. Westport, CT: The AVI Publishing Co.
- Vázquez, G., Chenlo, F., Moreira, R., & Costoyas, A. (1999). The dehydration of garlic. 1. Desorption isotherms and modelling of drying kinetics. *Drying Technology*, 17(6), 1095–1108.
- Waananen, K. M., Litchfield, J. B., & Okos, M. R. (1993). Classification of drying models for porous solids. *Drying Technology*, 11(1), 1–40.
- Wang, N., & Brennan, J. G. (1995). Changes in structure, density and porosity of potato during dehydration. *Journal of Food Engineering*, 24(1), 61–76.

- White, K. L., & Bell, L. N. (1999). Glucose loss and Maillard Browning in solids as affected by porosity and collapse. *Journal of Food Science*, 64(6), 1010–1014.
- Williams, M. L., Landel, R. F., & Ferry, J. D. (1955). The temperature dependence of relaxation mechanisms in amorphous polymers and other glass-forming liquids. *Journal of American Chemical Society*, 77, 3701–3707.
- Willis, B., Okos, M., & Campanella, O. (1999). Effects of glass transition on stress development during drying of a shrinking food system. In *Proceedings of the sixth conference of food engineering* (*CoFE*'99) (pp. 496–451). Dallas, TX.
- Zogzas, N. P., Maroulis, Z. B., & Marinos-Kouris, D. (1994). Densities, shrinkage and porosity of some vegetables during air drying. *Drying Technology*, 12(7), 1653–1666.