

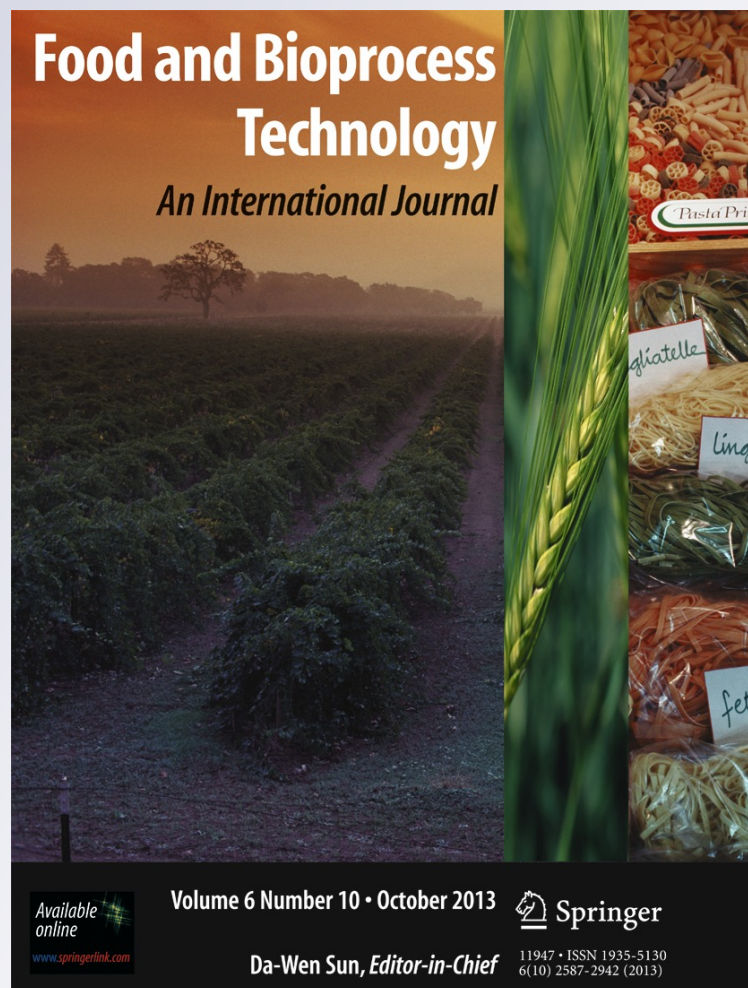
# *Osmotic Dehydration of Nectarines: Influence of the Operating Conditions and Determination of the Effective Diffusion Coefficients*

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# Osmotic Dehydration of Nectarines: Influence of the Operating Conditions and Determination of the Effective Diffusion Coefficients

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**Abstract** The aim of the present work is to study the kinetics of osmotic dehydration of Caldesi nectarines (*Prunus persica* var. *nectarina*) evaluating the effect of osmotic solution concentration, type of solute, temperature, fruit/solute ratio and process time on moisture content, water loss, soluble solids content and solids gain. The process analysis was carried out experimentally and numerically through the mathematical modelling of mass transfer. Hypertonic solutions of glucose syrup and sorbitol (40 and 60 % w/w) were used for dehydration, during 2 h of process at temperatures of 25 and 40 °C, with fruit/osmotic agent ratio of 1:4 and 1:10. Water loss and solids gain showed significant differences depending on the type and concentration of the osmotic agent, process time and fruit/solution ratio. The concentration interacted significantly with all variables; in addition, there was an interaction between the type of osmotic agent and the relationship between fruit and the osmotic agent. The effective diffusion coefficients were obtained from the analytical solution of Fick's second law applied to flat-plate geometry and by solving the mass transfer microscopic balances by finite element method, taking into account the real geometry of the nectarine pieces. The values obtained from Fick's law varied between  $1.27 \times$

$10^{-10}$  and  $1.37 \times 10^{-08} \text{ m}^2 \text{ s}^{-1}$  for water and from  $1.14 \times 10^{-10}$  to  $1.08 \times 10^{-08} \text{ m}^2 \text{ s}^{-1}$  for soluble solids, while the values calculated by finite elements method ranges were between  $0.70 \times 10^{-09}$  and  $4.80 \times 10^{-09} \text{ m}^2 \text{ s}^{-1}$  for water and between  $0.26 \times 10^{-09}$  and  $1.70 \times 10^{-09} \text{ m}^2 \text{ s}^{-1}$  for soluble solids. The diffusion coefficients values obtained from the numerical solution are consistent with those published in literature.

**Keywords** Osmotic dehydration · Diffusion coefficients · Nectarines

## Abbreviations

WL	Water loss (%)
SG	Solids gain (%)
WR	Weight reduction (%)
TS <sub>o</sub>	Initial content of total solids (%)
TS	Content of total solids (%)
W <sub>o</sub>	Initial mass of sample (g)
W	Sample mass (g)
D <sub>w</sub>	Effective diffusion coefficient of water ( $\text{m}^2 \text{ s}^{-1}$ )
D <sub>s</sub>	Effective diffusion coefficient of solute ( $\text{m}^2 \text{ s}^{-1}$ )
C <sub>w0</sub>	Initial moisture content (g of water/100 g of sample)
C <sub>w</sub>	Moisture Content (g of water/100 g of sample)
C <sub>w∞</sub>	Moisture content at equilibrium (%)
C	Concentration ( $\text{kgm}^{-3}$ )
L	Half-thickness (m)
ARE	Average relative error (dimensionless)
t	Time of process (min)

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## Introduction

In the last years, studies on stone fruits dehydration such as plums (Franklin et al. 2006; Tarhan 2007), cherries (Goncalves et al. 2007; De Michelis et al. 2008), peaches (Gil et al. 2002),

apricots (Khoyi and Hesari 2007; Ispir and Togrul 2009) and nectarines (Araujo et al. 2004) have been performed due to the nutritional properties of these fruits and the interest of obtaining a long shelf-life with the best possible quality.

Nectarines are stone fruits, the production and merchandising of which are similar to peaches; their nutritional properties are also similar, whereas nectarines have slightly higher contents of provitamin A and vitamin E. They also stand out for their high content of potassium (Gil et al. 2002; Lavelli et al. 2009). Both fruits contain considerable amounts of antioxidants, including hydroxycinnamic acid, flavonoids, anthocyanins and carotenoids. Besides the benefits for consumer health, many of these compounds are responsible for the attractive colour of the fruits (Lavelli et al. 2009).

The osmotic dehydration (OD) is used as a pretreatment to many processes as it improves the nutritional, sensory and functional properties of processed foods without affecting their good condition (Torreggiani 1993). This technique consists in the immersion of fruits or vegetables (whole or in pieces) in solutions of sugars, salts, combinations of both or alcohols. It is characterised by flux exchange of water and solutes permitting the fruit to lose water and gain solids, depending on the process conditions (Ramallo and Mascheroni 2005; Shi et al. 2009). The presence of simultaneous and opposite fluxes is one of the main difficulties in modelling osmotic dehydration kinetics (Spiazzi and Mascheroni 1997).

The speed of product water loss and the changes to its chemical composition depend on the nature and size of the product to dehydrate, on the type and concentration of the osmotic agent, on the fruit/syrup ratio, on temperature and process time. The periodical shaking of the system also produces a significant increase on the dehydration rate (Maldonado et al. 2008). In general, within the first 2 h of contact between the fruit and the syrup, a high speed of water removal is achieved; after this period, speed starts to decrease due to a less difference of osmotic pressure and a greater resistance to mass transfer at this stage of the process (Barbosa Cánovas and Vega Mercado 2000).

In many works, models to predict mass transfer kinetics of osmotic dehydration at atmospheric pressure have been presented. However, it is very difficult to develop a mathematical model capable of including all the factors involved in the process (Ispir and Togrul 2009). Some authors, such as Salvatori et al. (1999), have used Fick's law to explain the diffusion phenomenon, while other authors such as Spiazzi and Mascheroni (1997) have proposed models based on the knowledge of cellular physiology of tissues. Osmotic dehydration processes are generally designed with the objective of maximising water removal while the solids gain is limited, to obtain a product with little taste and flavour alteration regarding the fresh product. There is a single index that clearly indicates the direction of osmotic dehydration process called efficiency index of dehydration (Lazarides

2001), which is defined as the relationship between water loss and solids gain. This index has been widely used to evaluate efficiency of osmotic dehydration process, due to its easy interpretation. High values of efficiency index indicate that the process favours dehydration minimising solids gain, while low values indicate that the process promotes a greater solids gain with minimum water loss (Jokić et al. 2008).

As seen from above information, OD of nectarines has been barely studied and characterised (Araujo et al. 2004). Moreover, the determination of water transfer parameters in terms of diffusivity and water transfer coefficients for products subject to dehydration is essential to analyse efficiently the process and to optimise energy use.

The analytical solution of Fick's second law for unsteady state may be applied to calculate the effective diffusivity of moisture ( $D_w$ ); this is the best known procedure to represent the diffusional mechanism (Perumal 2007; Farid 2010). Most published studies usually consider any finite food geometry as infinite flat plate configuration, neglecting the diffusion in the other directions. Such assumption is good when thickness is very small compared to sides, indicating negligible peripheral diffusion. On the other hand, when thickness is of equal magnitude to length and width (parallelepiped, cubic and finite cylinder) or shape is irregular, this assumption is no longer valid because significant amount of diffusion takes place through peripheral sides as well (Ferrari et al. 2011).

As alternative, the coefficients should be evaluated considering the real geometry of the object, using numerical solution techniques to solve the differential equations that characterise the process.

According to the above-stated, the objectives of the present work include the following:

- To study the osmotic dehydration kinetics of nectarines evaluating the effect of operating conditions (osmotic solution concentration, temperature, fruit/solution relationship, type of solute and process time) on the process characteristic variables (moisture content, water loss, soluble solids content and solids gain)
- To determine and compare the effective diffusion coefficients of water and solutes transfer, calculated by Fick's law analytical solution and by computational tools, which allow consider the real shape of nectarines pieces.

## Materials and Methods

### Samples Characterisation and Preparation

Nectarines var. Caldesi (*Prunus persica* var. *nectarina*) acquired in a local market (Olavarría, Argentina) were used. The fruits were kept refrigerated at 5 °C; before the test, samples selected by size and quality were washed and dried



with absorbent paper; then they were peeled, and the stones were removed; finally, they were manually cut into pieces of 1/16 (average weight 3.2 g) (Fig. 1a).

The initial moisture content of the fruit was 82.14 % wet basis; it was determined using a standard method (AOAC 1980) drying the fruit to constant weight in an oven at 70±2 °C. The initial content of soluble solids was 14.50 °Brix, determined with an Abbe refractometer (accuracy±0.01) (AOAC 1980).

Osmotic Dehydration

Osmotic dehydration was carried out during 2 h—period of high speed of water removal (Barbosa Cánovas and Vega Mercado 2000)—by immersing the samples in glucose syrup (C<sub>6</sub>H<sub>12</sub>O<sub>6</sub>) or sorbitol (C<sub>6</sub>H<sub>14</sub>O<sub>6</sub>) solutions prepared at 40 and 60 % w/w in distilled water, from glucose syrup at 82 % w/w and sorbitol at 67 % w/w, using an erlenmeyer of 2 L and a fruit/syrup ratio of 1:4 and 1:10. The samples were kept into the solution using a stainless steel mesh to prevent flotation. Two temperatures were tested, 25 and 40 °C, with a constant shaking system at 331 rpm. All the experiments were conducted in duplicate.

The samples weight (analytical balance, Mettler AE240, accuracy±0.0001 g), the moisture content (g of water/100 g of sample) and soluble solids content (g of soluble solids/100 g of sample) were evaluated at regular intervals.

To determine the water loss (WL<sub>t</sub>), solids gain (SG<sub>t</sub>) and weight reduction (WR<sub>t</sub>) as a function of time *t*, the following equations were used, respectively:

$$WL_t(\%) = \left[ \left( 1 - \frac{TS_0}{100} \right) - \left( 1 - \frac{TS_t}{100} \right) \left( 1 - \frac{WR_t}{100} \right) \right] 100 \quad (1)$$

$$SG_t(\%) = \left[ \left( 1 - \frac{WR_t}{100} \right) \frac{TS_t}{100} - \frac{TS_0}{100} \right] 100 \quad (2)$$

$$WR_t(\%) = \left( \frac{W_o - W_t}{W_o} \right) 100 \quad (3)$$

where TS<sub>0</sub> is the initial total solids of sample, TS<sub>t</sub> is the total solids present in sample at time *t*, W<sub>0</sub> is the initial mass of sample and W<sub>t</sub> is the mass of sample at time *t*.

Modelling of Mass Transfer

Phenomenological Models

To describe mass transfer during the OD process, the following microscopic balances were set for moisture and solids with a different degree of detail and accuracy:

$$\frac{\partial C_w}{\partial t} = \nabla(D_w \nabla C_w) \quad (4)$$

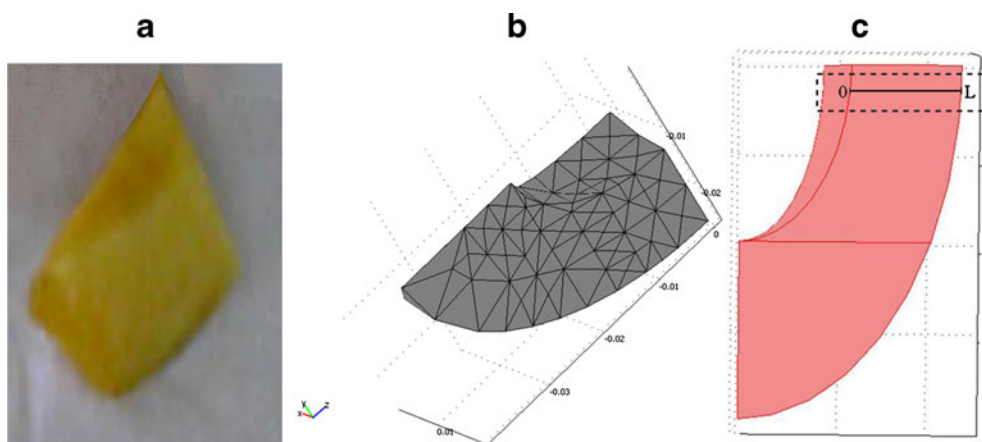
$$\frac{\partial C_s}{\partial t} = \nabla(D_s \nabla C_s) \quad (5)$$

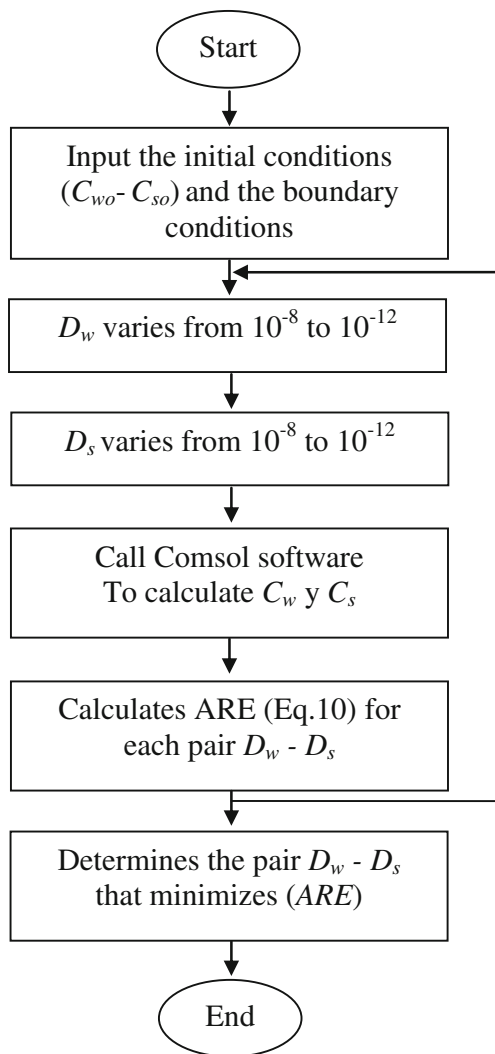
where *C* is the concentration (kg m<sup>-3</sup>), *t* is the time, *D* is the apparent diffusion coefficient and subscripts w and s represent water and soluble solids, respectively.

*Assumption of Regular Geometry* These expressions may be analytically solved considering constant properties, uniform initial conditions and constant concentration of water and soluble solids at boundary (surface). In this way, they may be analytically solved for regular semi-infinite media, such as infinite slabs, infinite cylinders and spheres (Crank 1975). A diagram of real geometry of a nectarine piece is presented in Fig. 1c (top view of a cross-section), and the analytical solution of the equations was obtained considering each piece as a slab.

The following assumptions were done for the analytical solution: (1) mass transfer is unidirectional, (2) solution concentration is constant in time, (3) diffusive mechanism of water removal is considered as valid, (4) fluxes interaction is not considered, (5) shrinking and external resistance to mass transfer are dismissed and (6) a slab equivalent to 12.5 mm of thickness is assumed.

**Fig. 1** Piece of fruit analyzed (a), 3D model used to simulate the OD process (b) and equivalent infinite slab used to determine the diffusion coefficients (c)





**Fig. 2** Block diagram for the calculation of  $D_w$  and  $D_s$  for operating condition

In osmotic dehydration, shrinkage of the pieces of fruit is almost negligible, since the material loses water while incorporating soluble solids (Lozano et al. 1983; Pani et al. 2008; Riva et al. 2008).

Crank's solution for average concentration in semi-infinite slabs is presented below:

$$\frac{(C_{wt} - C_{w\infty})}{(C_{wo} - C_{w\infty})} = \sum_{n=0}^{\infty} \frac{8}{(2n + 1)^2 \pi^2} \exp\left(- (2n + 1)^2 \frac{\pi^2 D_w}{4l^2} t\right) \quad (6)$$

The model may be simplified at long times, using just the first term of the above equation, and the following mathematical expression can be obtained (Eq. 7).

$$\frac{(C_{wt} - C_{w\infty})}{(C_{wo} - C_{w\infty})} = \frac{8}{\pi^2} \exp\left(- \frac{\pi^2 D_w}{4l^2} t\right) \quad (7)$$

Finally, from Eq. 7 the following expression is deduced:

$$\left[ \ln \frac{(C_{wt} - C_{w\infty})}{(C_{wo} - C_{w\infty})} \right] = \left( \ln \frac{8}{\pi^2} \right) + \left( - \frac{\pi^2 D_w}{4l^2} \right) t \quad (8)$$

where  $C_{wt}$  is the water concentration at time  $t$ ,  $C_{wo}$  is the initial water concentration,  $l$  is the half-thickness of the sample and  $C_{w\infty}$  is the equilibrium concentration value, which may be determined from Azuara's empirical model (Azuara et al. 1992).

Equation 5 was solved with the same procedure applied to Eq. 4, where the variable  $C_w$  is replaced by  $C_s$  in Eqs. 6, 7 and 8.

Knowing the experimental average values of moisture and solids content in the product and using Eq. 8, the diffusion coefficients of water and solids in the product may be calculated.

The average relative error (ARE) (Eq. 9) was used to estimate the quality of model adjustment.

$$ARE_j = \sum_i \left| \frac{C_j^{\text{exp}} - C_j^{\text{cal}}}{C_j^{\text{exp}}} \right| \quad (9)$$

where  $C$  is the concentration, the subscript  $j$  indicates water or solids, the subscript exp refers to experimental, while cal to calculated and the counter  $i$  indicates that the sum is made for discrete time steps in which experimental data are available.

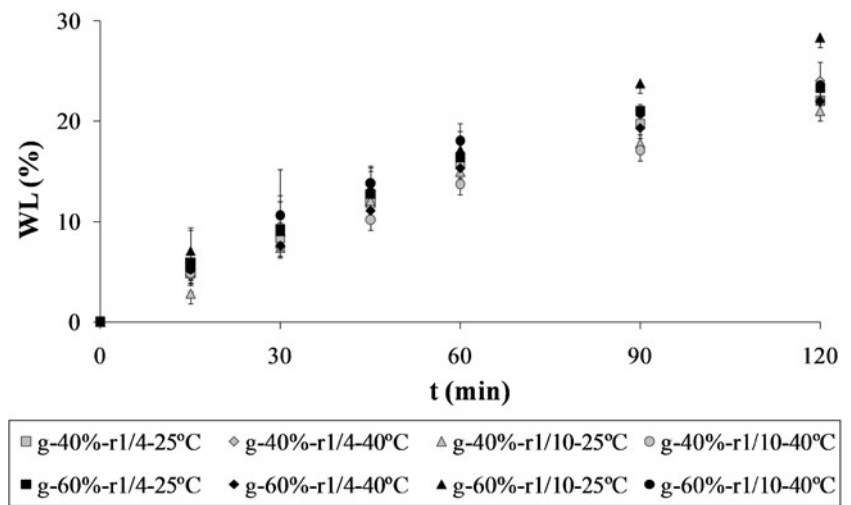
**Assumption of Real Geometry** The real geometry of the product must be considered for a more accurate calculation of moisture and solids profiles. With this purpose, Eqs. 4 and 5 were solved numerically with the finite elements method (FEM) using a commercial software (Comsol Multiphysics 3.5a), assuming as valid the assumptions 2–5 made in the previous section.

Figure 1b shows a diagram of the nectarine piece, which was submitted to osmotic dehydration modelling.

The solution of Eqs. 4 and 5 permits to obtain the moisture and solids profiles in the product, from which the effective diffusion coefficients of water and solids may be calculated. The software Matlab 7.10.0 was used for their determination, which considers different combinations of  $D_w$  and  $D_s$  in a known range ( $10^{-08}$ – $10^{-12} \text{ m}^2 \text{ s}^{-1}$ ), these interval values were selected according to previous values presented in the current literature (Panagiotou et al. 2004).

Then, the numerical solutions for these combinations were obtained with the assistance of Comsol software. The experimental runs could be compared with the numerical solution ( $C_w$  and  $C_s$  as a function of process time) through

**Fig. 3** Water loss of osmodehydrated nectarines in glucose syrup solution



the average relative error (Eq. 9). The following error function was built for each pair  $D_w-D_s$ :

$$ARE = ARE_w + ARE_s \tag{10}$$

The pair that minimised the error function (Eq. 10) was considered valid for the selected operating conditions.

The block diagram (Fig. 2) shows the calculation sequence to obtain the  $D_w$  and  $D_s$  coefficients, using the numerical scheme.

Statistical Data Analysis

The statistical study of the results was performed using the analysis of variance (ANOVA) with a significance level (SL) of 5 % or  $p < 0.05$ . Significant differences ( $p < 0.05$ ) between the paired means were determined using  $t$  test. The

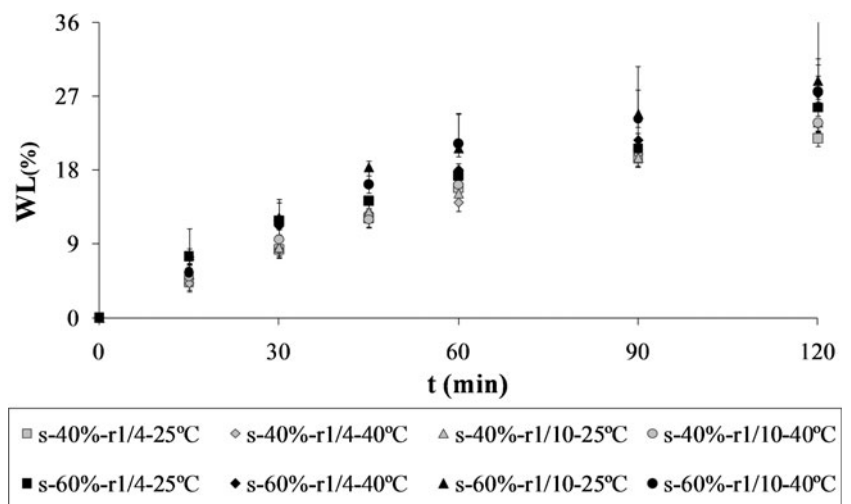
statistical analysis was performed using the InfoStat software (Di Rienzo et al. 2008).

Results and Discussion

Water Loss Kinetics during Osmotic Dehydration

Moisture content and water loss of samples dehydrated for 120 min in glucose syrup and sorbitol solutions are shown in Figs. 3 and 4, respectively. The graphs show the kinetics of WL for the 16 different treatments, varying the operating conditions: concentration of glucose (g-40 % and g-60 %) and sorbitol (s-40 % and s-60 %), osmotic agents, fruit/syrup ratio (r1/4 and r1/10) and process temperature (25 and 40 °C). The values of standard deviation between the duplicates are included as vertical bars in the same figures.

**Fig. 4** Water loss of osmodehydrated nectarines in sorbitol solution



**Table 1** Analysis of variance of the variables involved in osmotic dehydration of nectarines for WL and SG

Variables	WL			SG		
	<i>df</i> <sup>a</sup>	<i>F</i>	<i>p</i> value	<i>df</i> <sup>a</sup>	<i>F</i>	<i>p</i> value
Time (TIME)	6	1144.94	<0.0001	6	54.77	<0.0001
Type of osmotic agent (OA)	1	45.89	<0.0001	1	45.83	<0.0001
Concentration (CONOA)	1	126.64	<0.0001	1	127.35	<0.0001
Relationship between fruit and osmotic agent (FROA)	1	11.15	0.0013	1	11.73	0.0010
Temperature (TOD)	1	1.68	0.1995	1	1.86	0.1768
TIME×OA	1	2.03	0.0725	1	2.12	0.0612
TIME×CONOA	1	4.09	0.0014	1	4.19	0.0012
TIME×FROA	1	0.98	0.4465	1	0.92	0.4826
TIME×TOD	1	0.26	0.9522	1	0.29	0.9410
OA×CONOA	1	12.33	0.0008	1	12.95	0.0006
OA×FROA	1	5.08	0.0274	1	4.89	0.0302
OA×TOD	1	1.34	0.2513	1	1.50	0.2247
CONOA×FROA	1	24.24	<0.0001	1	24.05	<0.0001
CONOA×TOD	1	4.38	0.0400	1	4.20	0.0441
FROA×TOD	1	0.65	0.4229	1	0.76	0.3865

<sup>a</sup> *df* degree of freedom

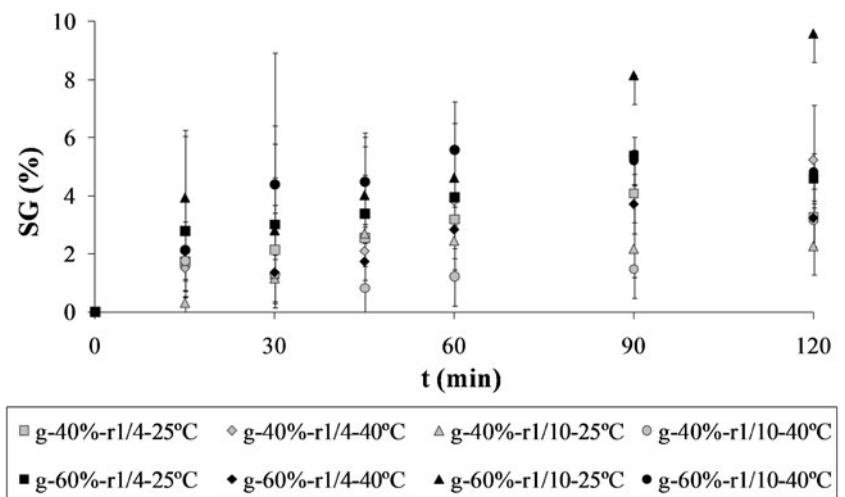
The statistical results of the analysis of variance performed to evaluate the effect of the treatments on water loss are shown in Table 1. The independent variables, the degrees of freedom (*df*), the critical values of Fisher (*F*) and the *p* values are displayed in the same table.

It was observed that the use of different agents determines significant differences ( $p < 0.0001$ ) in the results of WL, showing a greater degree of dehydration in those samples treated in sorbitol solution (Fig. 4). The interactions between the type of osmotic agent with its concentration ( $p = 0.0008$ ) and with the relationship between fruit and

osmotic agent ( $p = 0.0274$ ) affected the loss of water in nectarines.

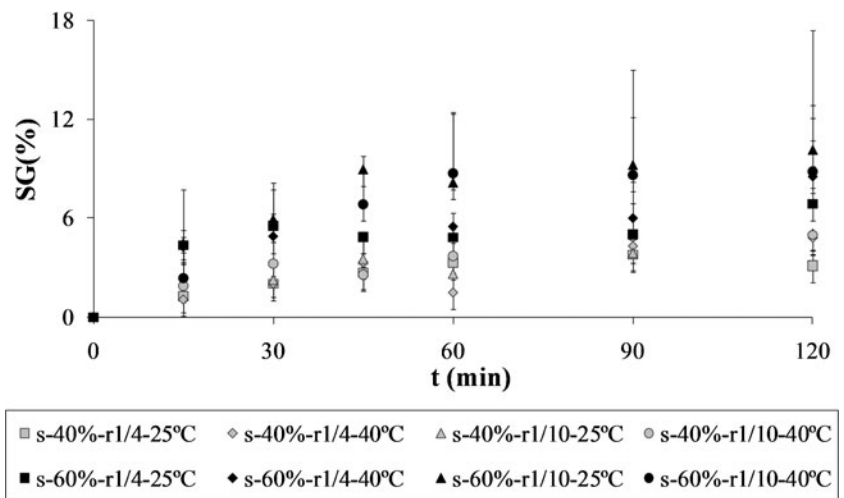
The increase in the concentration of hypertonic solution from 40 to 60 % *w/w* caused a greater water loss. This was a significant effect ( $p < 0.0001$ ), and it was more remarkable when sorbitol was used as a dehydrating agent (Fig. 4). These results are equivalent to those obtained by Araujo et al. (2004) and Ispir and Togrul (2009) in the OD of apricots in glucose, sorbitol, fructose, sucrose and maltodextrin solutions and by Ferrari et al. (2009) in the dehydration of pears in sucrose and sorbitol solutions. In addition, WL was

**Fig. 5** Soluble solids gain of osmodehydrated nectarines in glucose syrup solutions





**Fig. 6** Soluble solids gain of osmodehydrated nectarines in sorbitol solutions



affected by interactions of the concentration with process time ( $p=0.0014$ ), with the relationship between fruit and osmotic agent ( $p<0.0001$ ) and with osmotic treatment temperature ( $p=0.0400$ ) (Table 1).

Additionally, the increase in the proportion of solution from 4 to 10, with respect the sample allowed to obtain a higher water loss, leading to final products with less moisture content, for most of the studied conditions ( $p=0.0013$ ). Khoyi and Hesari (2007) stated that the increment of the ratio between syrup and fruit increases water loss during the dehydration of apricots, but ratios higher than 1:10 raise the process costs, becoming less suitable. The same deduction was reported by Ispir and Togrul (2009) for OD of apricots.

On the other hand, the temperature increase from 25 to 40 °C had no significant effect on water loss ( $p=0.1995$ ). These results are equivalent to those obtained by Fernandes et al. (2006) in the OD of bananas. Finally, the interactions between process time with type the osmotic agent ( $p=0.0725$ ), with the relationship between fruit and osmotic agent ( $p=0.4465$ ) and with temperature ( $p=0.9522$ ), as well as the interactions between the temperature with type of osmotic agent ( $p=0.2513$ ) and with the relationship between fruit and

osmotic agent ( $p=0.4229$ ) did not affect water loss of osmodehydrated nectarines (Table 1).

#### Solids Gain Kinetics during Osmotic Dehydration of Nectarines

Figures 5 and 6 show the evolution of soluble solids gain of osmodehydrated nectarines during 120 min in glucose and sorbitol solutions.

Table 1 shows the results of the analysis of variance for solids gain (SG) considering the data obtained during the osmotic dehydration of nectarines.

The samples showed significant differences ( $p<0.0001$ ) between the values of SG depending on the type of osmotic agent employed, reaching higher values when nectarines were immersed in a sorbitol solution (Fig. 6). The same way as for WL, the interactions between the type of osmotic agent and concentration ( $p=0.0006$ ) and with the relationship between fruit and osmotic agent ( $p=0.0302$ ) affected the solids gain.

The use of more concentrated hypertonic solutions permitted to obtain final products with a higher content of soluble solids as a result of a higher solids gain; these effects

**Table 2** Effect of the significant variables involved in OD of nectarines in water content and soluble solids content at 2 h

Operating conditions	Moisture content (%)			Soluble solids content (%)		
	Min	Max	SD	Min	Max	SD
OA glucose	66.21	75.23	2.81	21.50	30.05	2.75
OA sorbitol	65.55	74.18	3.00	22.50	31.00	2.69
FROA 1:4	67.56	74.18	2.35	22.00	28.50	2.29
FROA 1:10	65.55	75.23	3.70	21.50	31.00	3.57
CONOA 40 %	71.57	75.23	1.40	21.50	25.25	1.56
CONOA 60 %	65.55	74.04	3.18	22.00	31.00	3.22

SD standard deviation

**Table 3** Efficiency index of osmotic process of nectarines

Number	Condition	Efficiency index
1	g-40 %-r1/4-25 °C	6.73
2	g-40 %-r1/4-40 °C	4.58
3	g-40 %-r1/10-25 °C	9.26
4	g-40 %-r1/10-40 °C	6.91
5	g-60 %-r1/4-25 °C	5.07
6	g-60 %-r1/4-40 °C	6.80
7	g-60 %-r1/10-25 °C	2.95
8	g-60 %-r1/10-40 °C	4.89
9	s-40 %-r1/4-25 °C	7.00
10	s-40 %-r1/4-40 °C	4.91
11	s-40 %-r1/10-25 °C	4.73
12	s-40 %-r1/10-40 °C	4.77
13	s-60 %-r1/4-25 °C	3.74
14	s-60 %-r1/4-40 °C	3.21
15	s-60 %-r1/10-25 °C	2.85
16	s-60 %-r1/10-40 °C	3.13

were statistically significant ( $p < 0.0001$ ). In addition, SG was affected by interactions of the concentration with process time ( $p = 0.0012$ ), with the relationship between fruit and osmotic agent ( $p < 0.0001$ ) and with osmotic treatment temperature ( $p = 0.0441$ ) (Table 1).

Furthermore, the increase in the proportion of solution with respect the sample from 4 to 10 favored the solids gain ( $p = 0.0010$ ); this effect was more remarkable when using sorbitol as a dehydrating agent (Fig. 6).

Besides, SG was independent of the thermal bath temperature ( $p = 0.1768$ ). These data are consistent with those obtained by Ozen et al. (2002), where the author points out that temperature is a less important factor compared to other process variables. Ponting et al. (1966), Hawkes and Flink (1978), Islam and Flink (1982) and Fito et al. (1992) have also shown that a moderate increase in the osmotic solution temperature does not change the gain of solids.

Finally, as for the variable WL, the interactions between the process time with type of osmotic agent ( $p = 0.0612$ ), with the relationship between fruit and osmotic agent ( $p = 0.4826$ ) and with temperature ( $p = 0.9410$ ), as well as the interactions between the temperature and the type of osmotic agent ( $p = 0.2247$ ), and with the relationship between fruit and osmotic agent ( $p = 0.3865$ ) did not affect solids gain of nectarines (Table 1).

Finally, the relative influence of independent variables on the moisture and soluble solids content was analysed. Minimum, maximum and standard deviations for moisture content and soluble solid content were tabulated at final time (120 min) as function of the type of agent, fruit to syrup ratio and osmotic agent concentration (Table 2).

It is noteworthy that fresh nectarines had an initial water content of 82.14 % and initial soluble solids content of 14.15 % and, after 16 different osmotic treatments, were obtained products with moisture content values between 65.55 and 75.23 % and soluble solids contents between 21.50 and 31.00 %, depending on operating conditions. The ranges of these variables are not so wide even for very diverse dehydrating conditions. Regarding the final values of soluble solids for dehydrated samples in glucose syrup and sorbitol, the increase of soluble solids content was relevant due to the low molecular weight of both agents (180.16 and 182.17 g/mol, respectively), this fact facilitated the entry of the molecule to the fruit (Araujo et al. 2004; Ruiz-López et al. 2008).

The nature of the osmotic agent is essential to define the interaction of solutes with water and the solid matrix of the food. Comparing equal solute molecular weight, viscosity, depressing capacity of water activity and ionic behaviour are the variables that define the behavior of osmotic agents (Raoult-Wack et al. 1991; Cháfer et al. 2001; Emam-Djomeh et al. 2001; Moreira Azoubel & Murr 2004; Antonio et al. 2006; Borin et al. 2008; Quintero-Chávez et al. 2010).

#### Determination of Process Efficiency

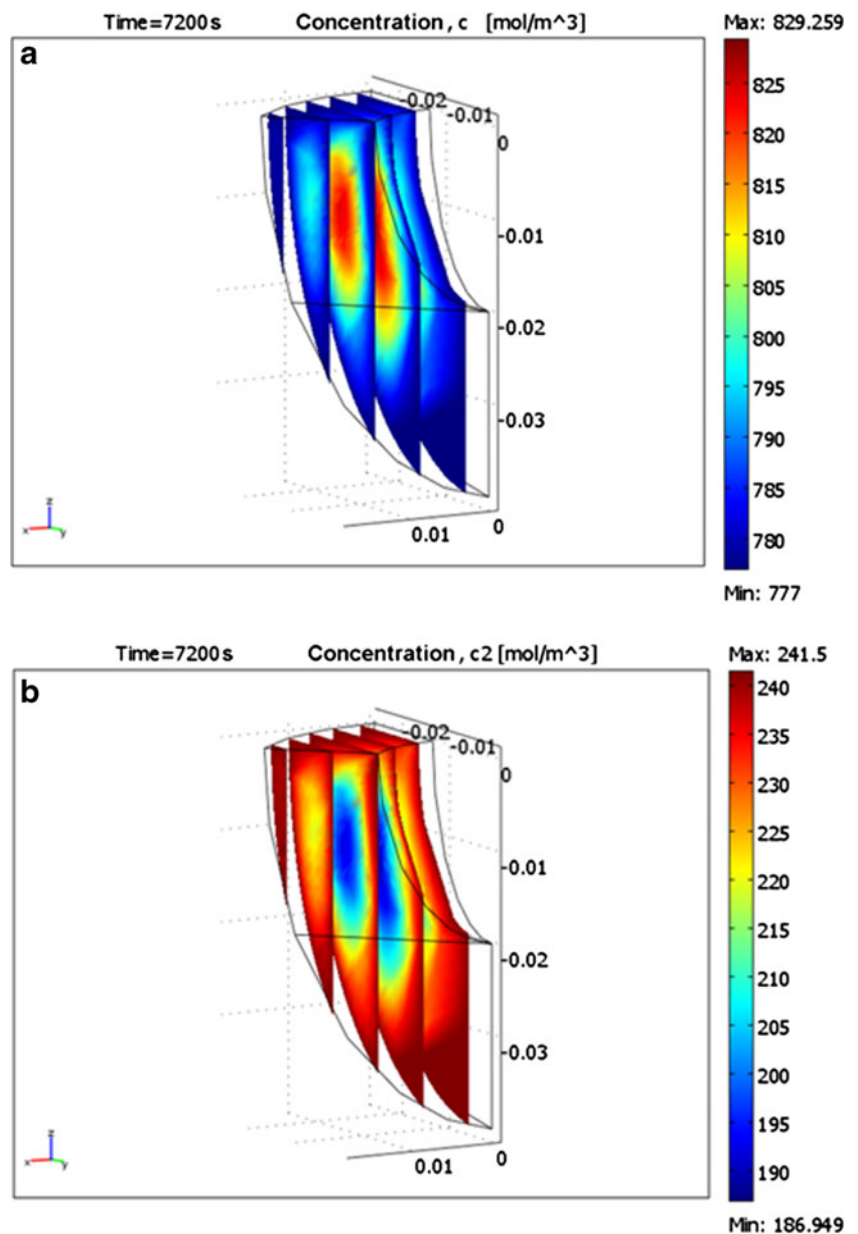
To evaluate the efficacy of osmotic process the efficiency index was calculated as the ratio of WL and SG (Lazarides 2001). Table 3 shows the obtained results for all operating conditions.

For all the studied conditions, the efficiency index was greater than unity; this indicates that the outflow of water from the fruit into the hypertonic solution was higher than the inward flux of solutes from the solution into the fruit. Therefore, osmodehydrated nectarines with slight modifications in flavour will be obtained due to the low intake of solute from osmotic syrup. The maximum value of efficiency was obtained for test 3 (9.26), when the samples were osmodehydrated in glucose syrup at 40 % w/w, with a fruit/syrup ratio of 1:10 and 25 °C, and the minimum value was for treatment 15 (2.85) when sorbitol solution at 60 %, ratio 1:10 and 25 °C were used.

The effect of concentration and process temperature on the efficiency index may be attributed to the collapse of the cell structure when working with high concentrations of osmotic solution and/or temperature causing a partial removal of osmotic solution with gas release, resulting in pores contraction and, consequently, reducing the free volume for the soluble solids impregnation (Barat et al. 2001).

The efficiency index of the samples osmodehydrated in glucose syrup 40 % w/w was higher at 25 °C, while for a concentration of 60 % w/w was more efficient at 40 °C, regardless of the ratio fruit/solution. For samples osmodehydrated in sorbitol, the efficiency index was higher at 25 °C when the ratio fruit/solution ratio was 1:4, while when the

**Fig. 7** Final profiles of moisture (a) and soluble solids (b) simulated during osmotic dehydration of nectarine pieces, in sorbitol syrup at 60 % w/w, using COMSOL-Multiphysics



ratio was 1:10, the process was more efficient at 40 °C, regardless of the concentration of osmotic agent.

Comparing the efficiency index in terms of the osmotic agent, it is observed in general that the process was more efficient for glucose, due to the osmodehydrated nectarines in sorbitol solution experimented more water loss and also more solids gain with the consequent decrease in the efficiency index. These results are consistent with those obtained by Ferrari et al. (2009) in the dehydration of pears in solutions of sucrose and sorbitol.

#### Effective Diffusion Coefficients of Water and Solids

Effective diffusion coefficients were obtained from the analytical solution of Fick's second law for semi-infinite slab and

from the numerical solution using the real geometry of the pieces. In the latter case, the concentration profiles of moisture and soluble solids inside the product were obtained. Typical water and soluble solids predicted concentration profiles using the real geometry are presented in Fig. 7.

Applying the described technique (for real geometry, Eq. 10), the parameters  $D_w$  and  $D_s$  that minimise the error function can be obtained.

Tables 4 and 5 show the effective diffusion coefficients of water ( $D_w$ ) and solids ( $D_s$ ), respectively, calculated using the analytical solution (Eq. 8) and those obtained using the numerical solution accompanied by their average relative errors (ARE).

The effective diffusion coefficient of water (Table 4) calculated from the analytical solution varied in a range

**Table 4** Effective diffusion coefficients of water

Number	Condition	$D_w$ ( $m^2 s^{-1}$ ) analytical solution	ARE	$D_w$ ( $m^2 s^{-1}$ ) numerical solution	ARE
1	g-40 %-r1/4-25 °C	$8.29 \times 10^{-09}$	0.01	$1.80 \times 10^{-09}$	0.07
2	g-40 %-r1/4-40 °C	$8.45 \times 10^{-09}$	0.03	$1.30 \times 10^{-09}$	0.12
3	g-40 %-r1/10-25 °C	$6.56 \times 10^{-09}$	0.01	$2.11 \times 10^{-09}$	0.13
4	g-40 %-r1/10-40 °C	$2.34 \times 10^{-09}$	0.003	$1.00 \times 10^{-09}$	0.06
5	g-60 %-r1/4-25 °C	$1.37 \times 10^{-08}$	0.03	$2.20 \times 10^{-09}$	0.13
6	g-60 %-r1/4-40 °C	$9.44 \times 10^{-09}$	0.02	$1.70 \times 10^{-09}$	0.08
7	g-60 %-r1/10-25 °C	$4.79 \times 10^{-09}$	0.03	$0.70 \times 10^{-09}$	0.13
8	g-60 %-r1/10-40 °C	$1.70 \times 10^{-10}$	0.02	$4.80 \times 10^{-09}$	0.11
9	s-40 %-r1/4-25 °C	$1.22 \times 10^{-08}$	0.02	$4.80 \times 10^{-09}$	0.11
10	s-40 %-r1/4-40 °C	$5.85 \times 10^{-09}$	0.02	$1.30 \times 10^{-09}$	0.10
11	s-40 %-r1/10-25 °C	$3.91 \times 10^{-09}$	0.009	$1.10 \times 10^{-09}$	0.07
12	s-40 %-r1/10-40 °C	$6.62 \times 10^{-09}$	0.02	$1.80 \times 10^{-09}$	0.14
13	s-60 %-r1/4-25 °C	$2.67 \times 10^{-09}$	0.01	$1.30 \times 10^{-09}$	0.06
14	s-60 %-r1/4-40 °C	$2.93 \times 10^{-09}$	0.003	$0.70 \times 10^{-09}$	0.07
15	s-60 %-r1/10-25 °C	$5.73 \times 10^{-09}$	0.01	$1.90 \times 10^{-09}$	0.09
16	s-60 %-r1/10-40 °C	$1.27 \times 10^{-10}$	0.02	$1.70 \times 10^{-09}$	0.12

between  $1.27 \times 10^{-10}$  and  $1.37 \times 10^{-08} m^2 s^{-1}$  with values of ARE lower than 0.03, which indicates a good quality of fit between predicted and experimental values, while those obtained with the numerical solution varied in the range of  $0.70 \times 10^{-09}$  and  $4.80 \times 10^{-09} m^2 s^{-1}$  with ARE values lower than 0.14.

The solids diffusion coefficients (Table 5) calculated from the analytical solution varied from  $1.14 \times 10^{-10}$  to  $1.08 \times 10^{-08} m^2 s^{-1}$  with ARE < 0.15, while those calculated from the numerical solution  $0.26 \times 10^{-09}$  and  $1.70 \times 10^{-09} m^2 s^{-1}$  with ARE < 0.14.

Moreover, the values of the diffusion coefficient of water and solids obtained by numerical solution fall within a narrower range of values compared with values obtained by analytical solution.

The analysis of paired mean through *t* test was employed to compare the diffusion coefficients of water and soluble solids obtained using analytical solution and numerical calculation.

The two-tailed *t* statistic for 15° of freedom and with a 95 % confidence is reported only as a positive value of 2.13. The values of experimental *t* obtained by comparing in pairs

**Table 5** Effective diffusion coefficients of solids

Number	Condition	$D_s$ ( $m^2 s^{-1}$ ) analytical solution	ARE	$D_s$ ( $m^2 s^{-1}$ ) numerical solution	ARE
1	g-40 %-r1/4-25 °C	$7.40 \times 10^{-09}$	0.06	$1.10 \times 10^{-09}$	0.07
2	g-40 %-r1/4-40 °C	$9.00 \times 10^{-09}$	0.15	$0.80 \times 10^{-09}$	0.12
3	g-40 %-r1/10-25 °C	$5.98 \times 10^{-09}$	0.07	$0.26 \times 10^{-09}$	0.13
4	g-40 %-r1/10-40 °C	$1.90 \times 10^{-09}$	0.01	$0.30 \times 10^{-09}$	0.06
5	g-60 %-r1/4-25 °C	$6.12 \times 10^{-09}$	0.03	$1.30 \times 10^{-09}$	0.13
6	g-60 %-r1/4-40 °C	$1.08 \times 10^{-08}$	0.11	$0.70 \times 10^{-09}$	0.08
7	g-60 %-r1/10-25 °C	$4.69 \times 10^{-09}$	0.11	$0.30 \times 10^{-09}$	0.13
8	g-60 %-r1/10-40 °C	$1.50 \times 10^{-10}$	0.05	$1.70 \times 10^{-09}$	0.11
9	s-40 %-r1/4-25 °C	$7.67 \times 10^{-09}$	0.07	$1.13 \times 10^{-09}$	0.11
10	s-40 %-r1/4-40 °C	$5.55 \times 10^{-09}$	0.10	$0.60 \times 10^{-09}$	0.10
11	s-40 %-r1/10-25 °C	$4.25 \times 10^{-09}$	0.05	$0.60 \times 10^{-09}$	0.07
12	s-40 %-r1/10-40 °C	$7.86 \times 10^{-09}$	0.07	$1.30 \times 10^{-09}$	0.14
13	s-60 %-r1/4-25 °C	$2.35 \times 10^{-09}$	0.06	$0.60 \times 10^{-09}$	0.06
14	s-60 %-r1/4-40 °C	$3.33 \times 10^{-09}$	0.02	$0.90 \times 10^{-09}$	0.12
15	s-60 %-r1/10-25 °C	$6.03 \times 10^{-09}$	0.05	$1.40 \times 10^{-09}$	0.09
16	s-60 %-r1/10-40 °C	$1.14 \times 10^{-10}$	0.08	$0.70 \times 10^{-09}$	0.07



the 16 diffusion coefficients of water and solids calculated for slab and real geometry were 4.12 and 5.65, respectively. Therefore, there are significant differences ( $p < 0.05$ ) between values determined by analytical and numerical calculation.

It can be observed (Tables 4 and 5) that in most processing conditions, the coefficients calculated by the analytical method are higher relative to those obtained by the numerical method. It can be explained considering that the fluxes assigned to a single direction overestimate the rate of diffusion for WL and SG values; to consider the real and irregular geometry involves a different spatial distribution and a lower rate of diffusion. The results obtained from the numerical solution are in agreement with those obtained by other authors. Besides, the diffusion coefficients from analytical solution differ in up to two orders of magnitude, which cannot be explained by differences in operating conditions. An analysis of variance was carried out to evaluate the influence of system variables on the diffusion coefficients, by which it was determined that the operating variables (type of osmotic agent, concentration, fruit/syrup ratio and temperature) did not exert a significant influence ( $p < 0.05$ ) on  $D_w$  and  $D_s$  values obtained from the two calculation techniques.

The results obtained by numerical simulation technique are consistent with published data. According to Ispir and Togrul (2009), the diffusion coefficients of water varied between  $0.77 \times 10^{-10}$  and  $1.75 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$  in OD of apricots, while Sabarez and Price (1999) obtained diffusion coefficients of water in the range of  $4.30 \times 10^{-10}$  and  $7.60 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$  in OD of plums. On the other hand, Khoyi and Hesari (2007) reported values between  $1.07 \times 10^{-09}$  and  $4.06 \times 10^{-09} \text{ m}^2 \text{ s}^{-1}$  for water diffusion and  $7.69 \times 10^{-10}$  and  $3.13 \times 10^{-09} \text{ m}^2 \text{ s}^{-1}$  for solids diffusion in apricots, using Fick's law for a slab. Moreover, diffusion coefficients obtained after 1 h of OD of apple tissue were  $1.53 \times 10^{-10}$  and  $1.05 \times 10^{-10} \text{ m}^2 \text{ s}^{-1}$  for water and solids, respectively (Azuara et al. 2009).

From the obtained values of diffusion coefficient using analytical solution and numerical inverse technique, it is possible to conclude that even though the analytical solution provides a better fitting of experimental data, the numerical solution provides more realistic coefficient values that are in agreement with previous works.

## Conclusions

During the osmotic dehydration of nectarines a reduction of the moisture content and an increment of the soluble solids content are produced, with a consequent increase of water loss and solids gain as a function of process time, type, osmotic agent concentration and fruit/osmotic solution ratio.

The concentration interacted significantly with all variables. In addition, there was an interaction between the type of osmotic agent and the relationship between fruit and the osmotic agent. The samples osmodehydrated during 120 min in sorbitol solution with fruit/solution ratio of 1:10 and concentration of 60 % underwent greater dehydration degree.

The temperature of the process does not evidence an influence on the moisture content, soluble solids content, water loss and solids gain, but the interaction between temperature and concentration has a significant effect. Anyhow, the lowest value of final moisture and the highest solid content were achieved at 25 °C; this was confirmed by determining the diffusion coefficient, where the water transfer from inside the fruit to the osmotic solution was higher when the process was carried out at room temperature.

Diffusional coefficients calculated by the analytical method for semi-infinite slab are higher relative to those calculated considering the real geometry, overestimating the rate of diffusion for the same values of WL and SG. The results obtained from the numerical solution are consistent with those published in literature.

The study of osmotic dehydration of nectarines makes possible to provide relevant information about a new fruit for drying industry and optimise the process based on the studied variables. It is noteworthy that osmotic dehydration is not a methodology to be applied alone, but must be accompanied by another preservation technique such as hot air drying permitting to reach the safe moisture level.

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