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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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INTRODUCTION

In the last years, studies on stone fruits dehydration such as plums (Flanklin et al., 2006; Tarhan et al., 2007), cherries (Goncalves et al., 2007; De Michelis et al., 2008), peaches (Gil et al., 2002), apricots (Khoyi et al., 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, which production and merchandising is 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 color of the fruits (Lavelli et al., 2009).

The osmotic dehydration (OD) is employed as a pre-treatment for many processes; it improves the nutritional, sensory and functional properties of processed foods without affecting their good condition (Quintero-Chávez et al., 2010). 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 caracterized 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 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 two hours 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 et al., 2000).

In many works, models to predict mass transfer kinetics of osmotic dehydration at atmospheric pressure have been developed. 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. The osmotic dehydration processes are generally designed with the objective of maximizing water removal while the solids gain is limited, to obtain a product with little 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 favors dehydration minimizing solids gain, while low values indicate that the process promotes a greater solids gain with minimun water loss (Jokié et al., 2008).

As can be seen from above information, OD of nectarines has been barely studied and characterized (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 analize efficiently the process and to optimize 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, finite cylinder), 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 characterize the process.

According to the above stated the objectives of the present work include:

- 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 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 characterization and preparation

Nectarines var. Caldesi (*Prunus persica var. nectarina*) acquired in a local market (Olavarria, Argentina) were used. The fruits were kept refrigerated at 5ºC; 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) (Figure 1a).

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

Osmotic Dehydration

Osmotic dehydration was carried out during 2 h - period of high speed of water removal (Barbosa-Cánovas et al., 2000) - by immersing the samples in glucose syrup ($C_6H_{12}O_6$) or sorbitol ($C_6H_{14}O_6$) solutions prepared at 40 and 60% w/w in distilled water, using an erlenmeyer of 2 L and a fruit/syrup ratio of 1/4 and 1/10. The samples were kept into the solution by using a stainless steel mesh to prevent flotation. Two temperatures were tested, 25 and 40ºC, with a constant shaking system at 331 rpm. All the experiments were conducted in duplicate.

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

To determine the water loss (WL_t), solids gain (SG_t) and weight reduction (WR_t) as a function of time t, the following equations were used, respectively:

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

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

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

where TS_o is the initial total solids of sample; TS_t is the total solids present in sample at time t; W_o is the initial mass of sample; W_t 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 may be set for moisture and solids with a different degree of detail and accuracy:

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

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

where *C* is the concentration (kg m^{-3}); *t* is the time, *D* is the apparent diffusion coefficient and subscripts *w* and *s* represent water and soluble solids, respectively.

a) 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). The analytical solution of the equations was obtained considering each piece as a slab shape (Figure 1c).

The following assumptions were done for the analytical solution: *i)* mass transfer is unidirectional; *ii)* solution concentration is constant in time; *iii)* diffusive mechanism of water removal is considered as valid; *iv)* fluxes interaction is not considered; *v)* shrinking and external resistance to mass transfer are dismissed; *vi)* a slab equivalent to 12.5 mm of thickness is assumed.

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

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

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).

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

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

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

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).

Eq. (5) was solved with the same procedure applied to Eq. (4), where the subscript *w* is replaced *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 the statistical parameter used to estimate the quality of model adjustment.

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

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.

b) 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 *ii-v* 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} $m^2\ s^{-1}$), 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 could be 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 the average relative error (Eq. 9). The following error function was built for each pair D_w-D_s:

$$ARE = ARE_w + ARE_s \qquad (10)$$

The pair which minimized 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-value<0.05. Significant differences (p<0.05) between the means were determined using Duncan Test and *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 minutes in glucose syrup and sorbitol solutions are shown in Figs. 3 and 4, respectively. The graphs show the kinetics of *WL* for the sixteen 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°C and 40°C). The values of standard deviation between the duplicates are included as vertical bars in the same figures.

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 (Figure 4). This was confirmed by Duncan Test (p<0.05) with mean values for *WL* of 12.13 and 13.42% for samples treated in glucose syrup and sorbitol, respectively, for all conditions of concentration, temperature, agent/fruit relationship and times tested.

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. 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. The mean values of Duncan Test were for *WL* of 11.70% for osmodehydrated samples in solutions of 40% w/w and 13.85% when the concentration was of 60% w/w, for both osmotic agents and all tested conditions of temperature, agent/fruit ratio and process times.

Additionally, the increase of solution/fruit ratio from 4 to 10 permitted to obtain a major water loss, leading to final products with less moisture content, for the most of the studied conditions (p=0.0099), obtaining a mean value of 12.67 and 13.09% for fruit/syrup ratio of 1/4 and 1/10, respectively, for both osmotic agents and all tested conditions of concentration, temperature and process times. Khoyi et al. (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.

Finally, the temperature increase from 25 to 40 °C had no significant effect on water loss (p=0.3108). These results are equivalent to those obtained by Fernandes et al. (2006) in the OD of bananas.

Solids gain kinetics during osmotic dehydration of nectarines

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

Table 2 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 (Figure 6). Mean values for *SG* calculated from Duncan Test were of 2.76% and 4.05% for osmodehydrated samples in glucose syrup and sorbitol solutions, respectively, for all conditions of concentration, temperature, agent/fruit relationship and times tested.

The use of more concentrated hypertonic solutions permitted to obtain final products with a higher content of soluble solids as a result of a major solids gain, these effects were statistically significant (p<0.0001). Mean values of *SG* were 2.34% and 4.48% for solutions prepared at 40 and 60% w/w, respectively, for both osmotic agents and all tested conditions of temperature, agent/fruit ratio and process times.

On the other hand, the increase of solution/fruit ratio favoured the solids gain (p=0.0085), this effect was more remarkable when using sorbitol as a dehydrating agent (Figure 6). Mean value for *SG* was 3.08% when using a fruit/solution ratio of 1/4 and 3.73% for the 1/10 ratio, for the osmotic agents and all tested conditions of concentration, temperature and process times.

Besides, *SG* was independent of the thermal bath temperature (p=0.2876). 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.

Finally, the relative influence of independent variables was analyzed on the moisture and soluble solids content. 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 3).

It is noteworthy that fresh nectarines had an initial water content of 82.14% and initial soluble solids content of 14.15% and after sixteen 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. 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).

Determination of Process Efficiency

To evaluate the efficiency of osmotic process the efficiency index was calculated as the ratio of *WL* and *SG* (Lazarides, 2001). Table 4 shows the obtained results for all operating conditions.

For the most of 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 entry of sugar from osmotic syrup. The maximum value of efficiency was obtained for test 3 (9.26), where the samples were osmodehydrated in glucose syrup at 40% w/w, with a fruit to syrup ratio of 1/10 and 25°C and the minimum value was for treatment 15 (2.85) where 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).

Comparing the efficiency index in terms of the osmotic agent, it is observed in general that the process was more efficient in glucose, due to the osmodesdehydrated nectarines in sorbitol solution experimented more water loss but 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 Figure 7.

Applying the described technique (for real geometry, Eq. 10), the parameters D_w and D_s that minimize the error function (Figure 8) can be obtained.

Tables 5 and 6 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 5) calculated from the analytical solution varied between 1.27×10^{-10} and 1.37×10^{-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 0.70×10^{-09} and 4.80×10^{-09} m^2 s^{-1} with ARE values lower than 0.14.

The solids diffusion coefficients (Table 6) calculated from the analytical solution varied from 1.14×10^{-10} to 1.08×10^{-08} m^2 s^{-1} with *ARE* lower than 0.15, while those calculated from the numerical solution 0.26×10^{-09} and 1.70×10^{-09} m^2 s^{-1} with *ARE* lower than 0.14.

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 degrees 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 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 determined values by analytical and numerical calculation.

It can be observed (Tables 5 and 6) 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 of mass, by which it was determined that the operating variables (type of osmotic agent, concentration, fruit to syrup ratio and temperature) did not exert a significant influence ($p<0.05$) on D_w and D_s and values obtained from the two calculation techniques.

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

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 to osmotic solution ratio. The samples osmodehydrated during 120 minutes in sorbitol solution with fruit to solution ratio of 1 to 10 and concentration of 60% obtained greater dehydration degree.

The temperature of the process does no evidence an influence on the moisture content, soluble solids content, water loss and solids gain. 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 optimize 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 moisture safety.

NOMENCLATURE

WL	Water loss (%)
SG	Solids gain (%)
WR	Weight reduction (%)
TS_o	Initial content of total solids (%)
TS	Content of total solids (%)
W_o	Initial mass of sample (g)
W	Sample mass (g)
D_w	Effective diffusion coefficient of water ($m^2\ s^{-1}$)
D_s	Effective diffusion coefficient of solute ($m^2\ s^{-1}$)
C_{wo}	Initial moisture content (g of water/100 g of sample)
C_w	Moisture Content (g of water/100 g of sample)
$C_{w\infty}$	Moisture content at equilibrium (%)
C	Concentration ($kg\ m^{-3}$)
L	Half-thickness (m)
ARE	Average relative error (dimensionless)
t	Time of process (min)

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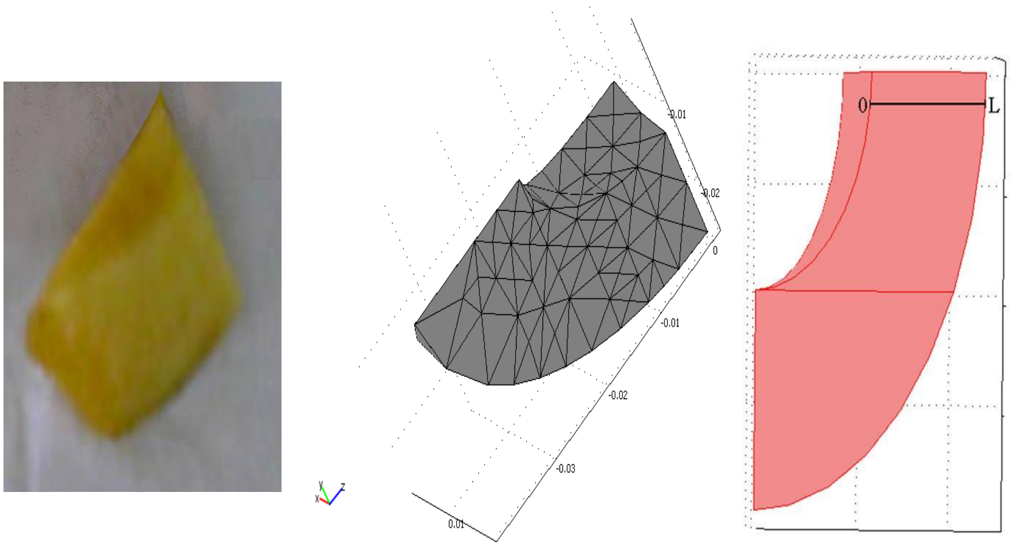


(a) **(b)** **(c)**

Figure 1.

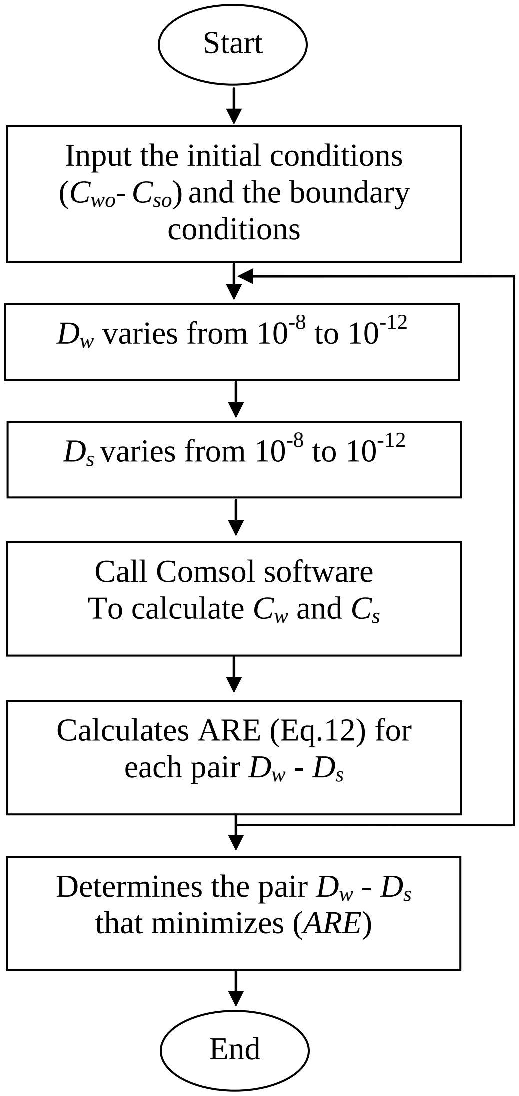
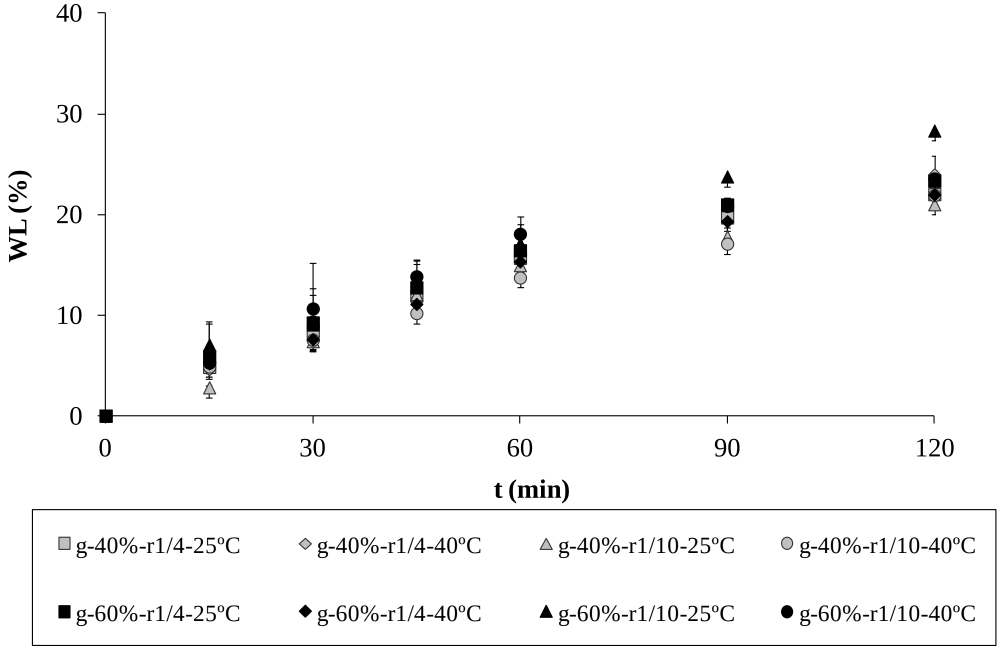

Start
Input the initial conditions (C_{wo}- C_{so}) and the boundary conditions
D_w varies from 10^{-8} to 10^{-12}
D_s varies from 10^{-8} to 10^{-12}
Call Comsol software To calculate C_w and C_s
Calculates ARE (Eq.12) for each pair D_w - D_s
Determines the pair D_w - D_s that minimizes (ARE)
End

Figure 2.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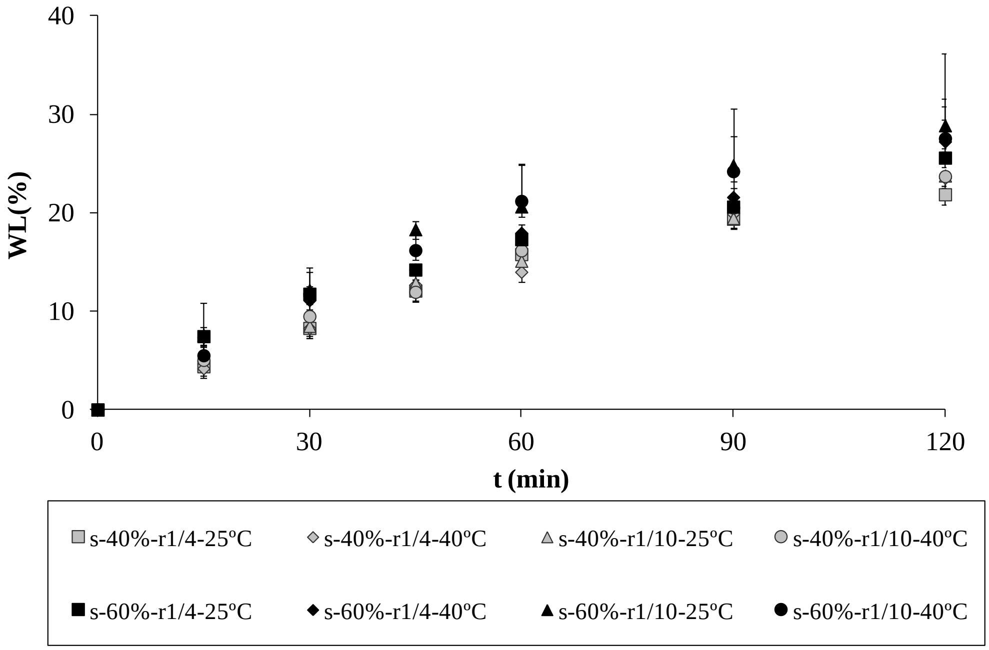
30
20
10
0
WL (%)
0
30
60
90
120
t (min)
g-40%-r1/4-25ºC
g-40%-r1/4-40ºC
g-40%-r1/10-25ºC
g-40%-r1/10-40ºC
g-60%-r1/4-25ºC
g-60%-r1/4-40ºC
g-60%-r1/10-25ºC
g-60%-r1/10-40ºC

Figure 3.


40
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WL(%)
0
30
60
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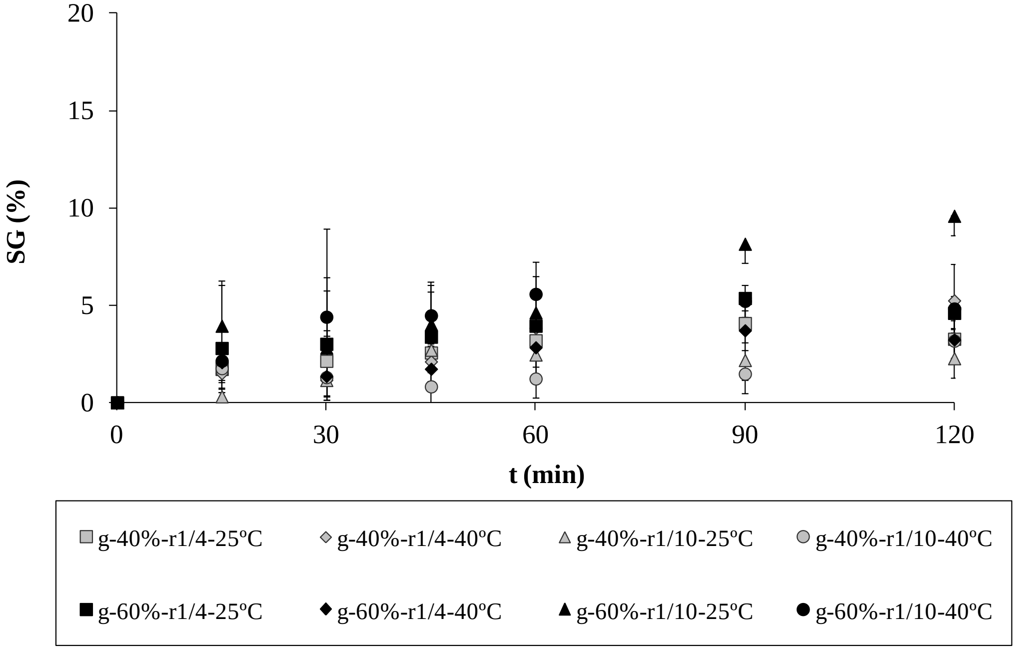
120
t (min)
s-40%-r1/4-25ºC
s-40%-r1/4-40ºC
s-40%-r1/10-25ºC
s-40%-r1/10-40ºC
s-60%-r1/4-25ºC
s-60%-r1/4-40ºC
s-60%-r1/10-25ºC
s-60%-r1/10-40ºC

Figure 4.


20
15
10
5
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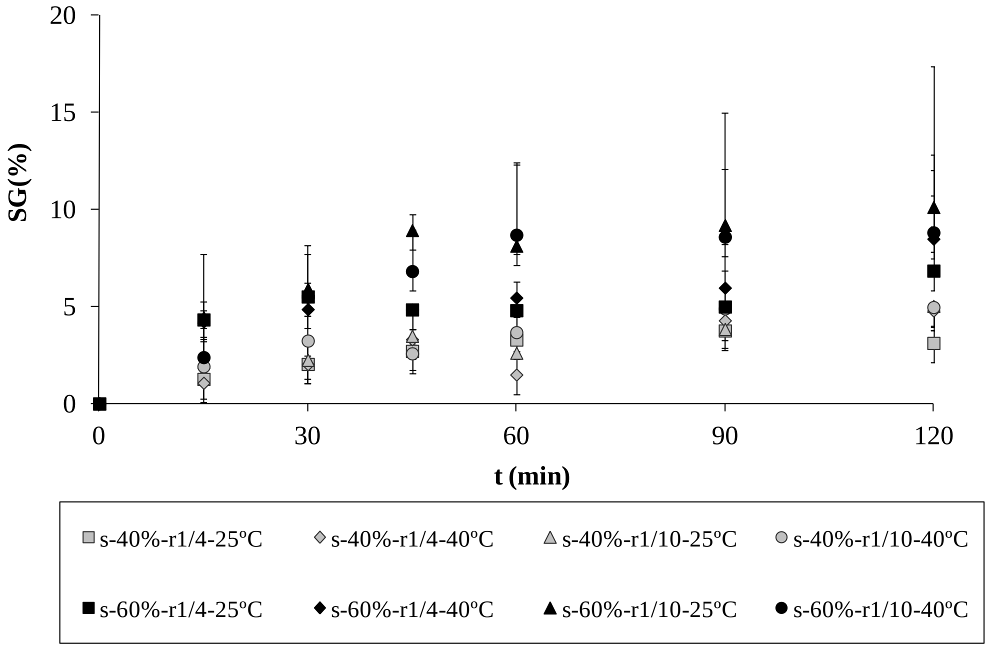
SG (%)
0
30
60
90
120
t (min)
□ g-40%-r1/4-25ºC
◇ g-40%-r1/4-40ºC
△ g-40%-r1/10-25ºC
○ g-40%-r1/10-40ºC
■ g-60%-r1/4-25ºC
◆ g-60%-r1/4-40ºC
▲ g-60%-r1/10-25ºC
● g-60%-r1/10-40ºC

Figure 5.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SG(%)
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t (min)
s-40%-r1/4-25ºC
s-40%-r1/4-40ºC
s-40%-r1/10-25ºC
s-40%-r1/10-40ºC
s-60%-r1/4-25ºC
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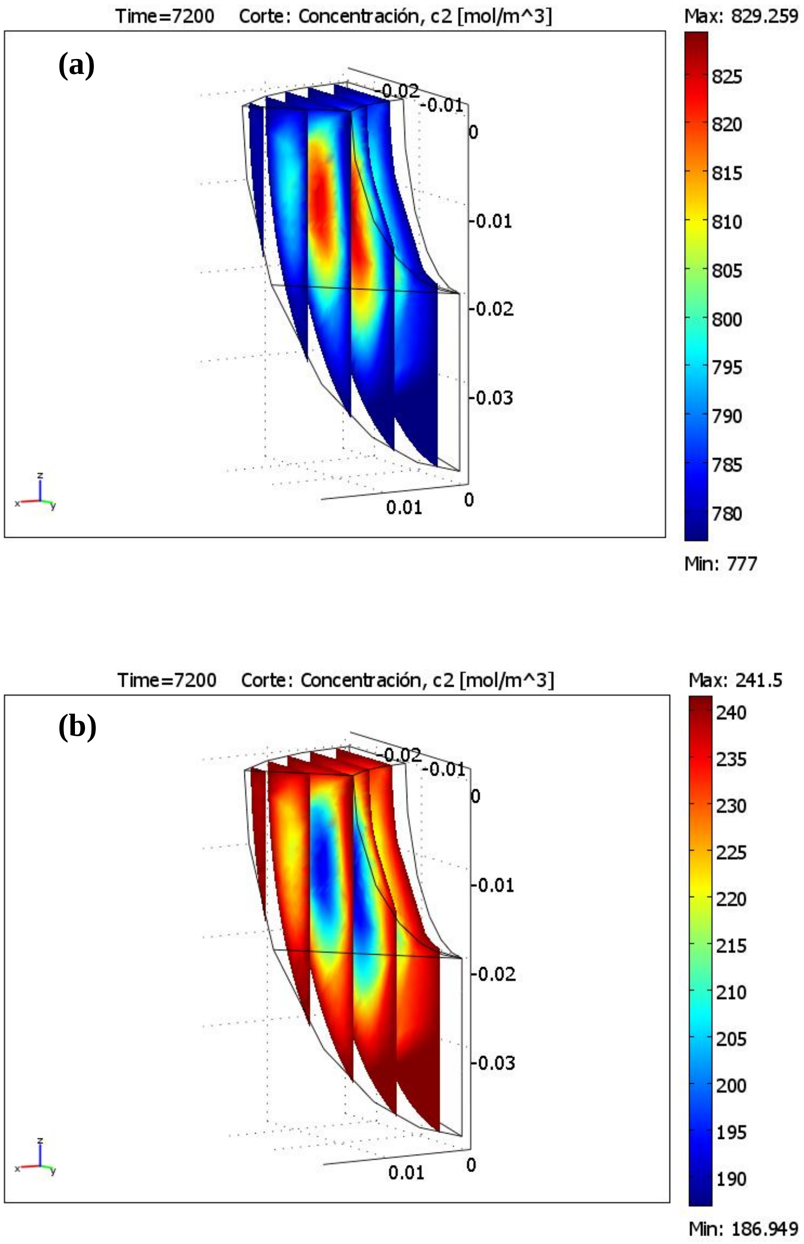
s-60%-r1/10-40ºC

Figure 6.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Max: 829.259
(a)
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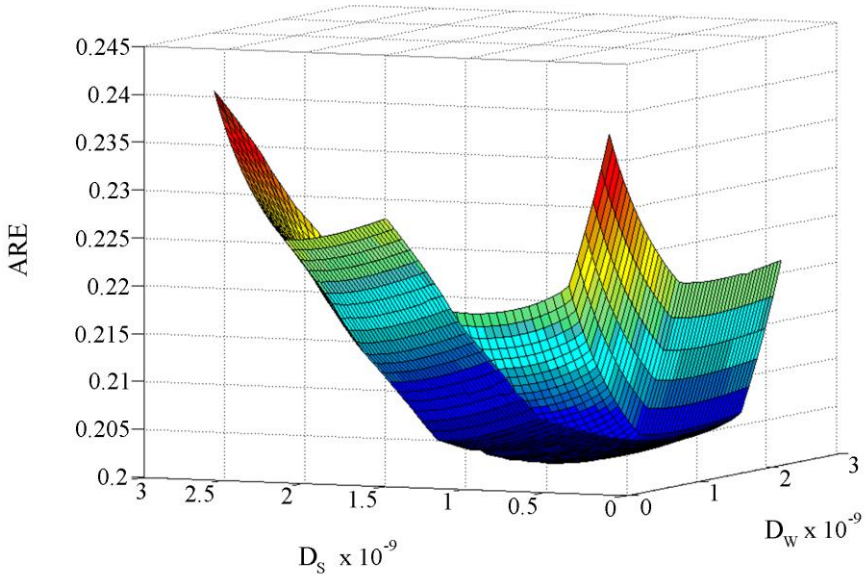
-0.01
0
-0.01
-0.02
-0.03
0.01
0
825
820
815
810
805
800
795
790
785
780
Min: 777
Time=7200 Corte: Concentración, c2 [mol/m^3]
Max: 241.5
(b)
-0.02
-0.01
0
-0.01
-0.02
-0.03
0.01
0
240
235
230
225
220
215
210
205
200
195
190
Min: 186.949
z
x
y

Figure 7.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0.24
0.235
0.23
0.225
0.22
0.215
0.21
0.205
0.2
ARE
3
2.5
2
1.5
1
0.5
0
$D_S \times 10^{-9}$
0
1
2
3
$D_W \times 10^{-9}$

Figure 8.

LEGENDS OF FIGURES

Figure 1 Photograph of a 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)**.

Figure 2. Block diagram for the calculation of D_w y D_s for each operating condition.

Figure 3. Water loss of osmodehydrated nectarines in glucose syrup solution.

Figure 4. Water loss of osmodehydrated nectarines in sorbitol solution.

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

Figure 6. Soluble solids gain of osmodehydrated nectarines in sorbitol solutions.

Figura 7. Final profiles of moisture **(a)** and soluble solids **(b)** simulated during osmotic dehydration of nectarine pieces, using COMSOL-Multiphysics.

Figure 8. Matrix of the error function (*ARE*) versus D_w and D_s for a selected processing condition: glucose 40%, r1/4 and 40ºC.

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

Variables	***WL***		
	Df*	F	p-value
Time (TIME)	6	708.54	<0.0001
Type of osmotic agent (OA)	1	28.40	<0.0001
Concentration (CONOA)	1	78.37	<0.0001
Fruit and osmotic agent ratio (FROA)	1	6.90	0.0099
Temperature (TOD)	1	1.04	0.3108

*Df, Degree of freedom

Table 2. Analysis of variance of the variables involved in osmotic dehydration of nectarines for *SG*.

Variables	***SG***		
	Df	F	p-value
Time (TIME)	6	33.63	<0.0001
Type of osmotic agent (OA)	1	28.14	<0.0001
Concentration (CONOA)	1	78.20	<0.0001
Fruit and osmotic agent ratio (FROA)	1	7.20	0.0085
Temperature (TOD)	1	1.14	0.2876

Table 3. 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 4. Efficiency Index of osmotic process of nectarines.

Nº	**Condition**	**Efficiency Index**
1	g-40%-r1/4-25ºC	6.73
2	g-40%-r1/4-40ºC	4.58
3	g-40%-r1/10-25ºC	9.26
4	g-40%-r1/10-40ºC	6.91
5	g-60%-r1/4-25ºC	5.07
6	g-60%-r1/4-40ºC	6.80
7	g-60%-r1/10-25ºC	2.95
8	g-60%-r1/10-40ºC	4.89
9	s-40%-r1/4-25ºC	7.00
10	s-40%-r1/4-40ºC	4.91
11	s-40%-r1/10-25ºC	4.73
12	s-40%-r1/10-40ºC	4.77
13	s-60%-r1/4-25ºC	3.74
14	s-60%-r1/4-40ºC	3.21
15	s-60%-r1/10-25ºC	2.85
16	s-60%-r1/10-40ºC	3.13

Table 5. Effective diffusion coefficients of water.

Nº	**Condition**	D_w (m^2 s^{-1}) Analytical Solution	***ARE***	D_w (m^2 s^{-1}) Numerical solution	***ARE***
1	g-40%-r1/4-25ºC	8.29x10^{-09}	0.01	1.80x10^{-09}	0.07
2	g-40%-r1/4-40ºC	8.45x10^{-09}	0.03	1.30x10^{-09}	0.12
3	g-40%-r1/10-25ºC	6.56x10^{-09}	0.01	2.11x10^{-09}	0.13
4	g-40%-r1/10-40ºC	2.34x10^{-09}	0.003	1.00x10^{-09}	0.06
5	g-60%-r1/4-25ºC	1.37x10^{-08}	0.03	2.20x10^{-09}	0.13
6	g-60%-r1/4-40ºC	9.44x10^{-09}	0.02	1.70x10^{-09}	0.08
7	g-60%-r1/10-25ºC	4.79x10^{-09}	0.03	0.70x10^{-09}	0.13
8	g-60%-r1/10-40ºC	1.70x10^{-10}	0.02	4.80x10^{-09}	0.11
9	s-40%-r1/4-25ºC	1.22x10^{-08}	0.02	4.80x10^{-09}	0.11
10	s-40%-r1/4-40ºC	5.85x10^{-09}	0.02	1.30x10^{-09}	0.10
11	s-40%-r1/10-25ºC	3.91x10^{-09}	0.009	1.10x10^{-09}	0.07
12	s-40%-r1/10-40ºC	6.62x10^{-09}	0.02	1.80x10^{-09}	0.14
13	s-60%-r1/4-25ºC	2.67x10^{-09}	0.01	1.30x10^{-09}	0.06
14	s-60%-r1/4-40ºC	2.93x10^{-09}	0.003	0.70x10^{-09}	0.07
15	s-60%-r1/10-25ºC	5.73x10^{-09}	0.01	1.90x10^{-09}	0.09
16	s-60%-r1/10-40ºC	1.27x10^{-10}	0.02	1.70x10^{-09}	0.12

Table 6. Effective diffusion coefficients of solids.

Nº	**Condition**	D_s (m^2 s^{-1}) Analytical solution	***ARE***	D_s (m^2 s^{-1}) Numerical solution	***ARE***
1	g-40%-r1/4-25ºC	7.40x10^{-09}	0.06	1.10x10^{-09}	0.07
2	g-40%-r1/4-40ºC	9.00x10^{-09}	0.15	0.80x10^{-09}	0.12
3	g-40%-r1/10-25ºC	5.98x10^{-09}	0.07	0.26x10^{-09}	0.13
4	g-40%-r1/10-40ºC	1.90x10^{-09}	0.01	0.30x10^{-09}	0.06
5	g-60%-r1/4-25ºC	6.12x10^{-09}	0.03	1.30x10^{-09}	0.13
6	g-60%-r1/4-40ºC	1.08x10^{-08}	0.11	0.70x10^{-09}	0.08
7	g-60%-r1/10-25ºC	4.69x10^{-09}	0.11	0.30x10^{-09}	0.13
8	g-60%-r1/10-40ºC	1.50x10^{-10}	0.05	1.70x10^{-09}	0.11
9	s-40%-r1/4-25ºC	7.67x10^{-09}	0.07	1.13x10^{-09}	0.11
10	s-40%-r1/4-40ºC	5.55x10^{-09}	0.10	0.60x10^{-09}	0.10
11	s-40%-r1/10-25ºC	4.25x10^{-09}	0.05	0.60x10^{-09}	0.07
12	s-40%-r1/10-40ºC	7.86x10^{-09}	0.07	1.30x10^{-09}	0.14
13	s-60%-r1/4-25ºC	2.35x10^{-09}	0.06	0.60x10^{-09}	0.06
14	s-60%-r1/4-40ºC	3.33x10^{-09}	0.02	0.90x10^{-09}	0.12
15	s-60%-r1/10-25ºC	6.03x10^{-09}	0.05	1.40x10^{-09}	0.09
16	s-60%-r1/10-40ºC	1.14x10^{-10}	0.08	0.70x10^{-09}	0.07