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Original article

Modelling of mass transfer and texture evaluation during osmotic dehydration of melon under vacuum

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Summary The influence of vacuum time and solution concentration on mass transfer and mechanical properties of osmodehydrated melon cubes has been studied. Pulsed vacuum osmotic dehydration (PVOD) was carried out at 30 °C for 4 h, using sucrose solutions (40, 50 or 60°Brix) and applying a vacuum pulse (100 mbar for 5, 10 or 15 min). Kinetics of water loss, solid gain and stress at rupture were analysed, as well as effective diffusivities using the hydrodynamic model. The increase in solution concentration favoured water removal, but no significant effect of vacuum time was observed. The use of less concentrated solutions coupled to the action of vacuum pulse resulted in greater solid uptake. Samples subjected to PVOD using 60°Brix sucrose solution presented greater water loss, lower sugar uptake and better maintenance of fresh fruit texture throughout the process. Diffusion coefficients estimated by the hydrodynamic model showed a good fit to the experimental data.

Keywords *Cucumis melo* L., effective diffusivity, hydrodynamic model, pulsed vacuum osmotic dehydration, stress at rupture, sucrose solution.

Introduction

Osmotic dehydration is a mild process that consists of immersing fruit pieces in a sugar-concentrated solution, where both partial dehydration of the tissue and solid uptake occur. The process can be used to take better advantage of availability of fruits and in some cases to improve final product soluble solid content, as a pretreatment to drying (Teles *et al*., 2006; Lombard *et al*., 2008), freezing (Blanda *et al*., 2009; Ramallo & Mascheroni, 2010) and frying (Taiwo & Baik, 2007). Moreover, osmotic process can be employed in the development of minimally processed products (Rodrigues *et al*., 2006; Torres *et al*., 2008; Moraga *et al*., 2009), prolonging their shelf life, with a slight reduction in fruit water activity and improving the microbiological stability, without changing considerably the quality characteristics of fresh fruit.

Pulsed vacuum osmotic dehydration (PVOD) involves the application of a subatmospheric pressure to the solid–liquid system at the beginning of process, which provides beneficial effects on process kinetics and also on quality of many fruits, helping to reduce energy costs (Fito, 1994; Fito *et al*., 2001). Water loss and solid gain are higher at the beginning of PVOD process, when the hydrodynamic mechanisms (HDM) take place, in comparison with osmotic process at atmospheric pressure (OD). The HDM is promoted by pressure gradients, owing to the combined action of capillary pressure and imposed or generated pressure changes on the porous structure of vegetable tissue. When the vacuum pressure is applied, the gas or liquid occluded in the intercellular spaces is removed, and as soon as the atmospheric pressure is restored, it is replaced by the external liquid (osmotic solution), that is, an outflow of internal gas or liquid from the tissue and the entrance of external solution are established, promoting water loss and external solution uptake (Fito & Chiralt, 1997). PVOD has been reported to increase mass transfer rates during the osmotic dehydration of apples (Paes *et al*., 2007; Deng & Zhao, 2008), pineapples (Lombard *et al*., 2008), guavas (Panadés *et al*., 2008; Corrêa *et al*., 2010), papayas (Moreno *et al*., 2004) and mangoes (Ito *et al*., 2007). Nevertheless, there are no available works in literature, concerning the influence of PVOD process on mass transfer kinetics and texture characteristics of melon (*Cucumis melo inodorus* variety).

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The main factors that affect osmotic process kinetics depend on process parameters, such as solution composition and concentration, temperature, immersion time, agitation degree, and vacuum time, as well as raw material characteristics, such as tissue microstructure, maturity state, shape and size (Chiralt & Fito, 2003). Water loss and sugar impregnation occurring during the osmotic dehydration may provide changes in mechanical properties, depending on process conditions and product characteristics, as a result of the modifications observed in cell structure throughout the process, involving loss of cell turgor pressure, deformation of cell wall, plasmolysis and tissue shrinkage, which modify the product appearance and texture features (Chiralt *et al*., 2001). Furthermore, the vacuum pulse application has an influence on fruit texture and tissue structural characteristics, as a result of the substitution of air in the intercellular spaces by the osmotic solution (Moreno *et al*., 2004).

Most of the models for mass transfer evaluation during the osmotic process are based on the mathematical solutions of Fick's second law, given by Crank (1975) for several product shapes and boundary conditions, allowing the determination of water and solid diffusion coefficients. However, according to Aguilera *et al*. (2003) and Matusek *et al*. (2008), PVOD is not a simple diffusion process and the hydrodynamic transport of water and solutes, owing to pressure gradients and capillary forces in open pores, is the predominant mass transfer mechanism. Other less relevant mechanisms include intercellular transport in liquid phase through plasmodesma, transmembrane flow and Fickian diffusion within non-compartmentalised zones. Thus, the increased mass transfer rate, because of the vacuum application, cannot be explained using the classical diffusive mechanisms, and the consideration of the hydrodynamic mechanism coupled with Fick's diffusion law provides a better representation of mass transfer phenomena during PVOD process (Fito, 1994). 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 (thickness $\ll$ sides), indicating negligible peripheral diffusion. On the other hand, when thickness is of equal magnitude to length and breadth (parallelepiped or cube), this assumption is no longer valid, because significant amount of diffusion takes place through peripheral sides as well (Rastogi & Raghavarao, 2004). There are not any available papers concerning the evaluation of mass transfer kinetics during PVOD process for cubical configuration, using the hydrodynamic model (HDM) proposed by Fito & Chiralt (1997).

The aim of this work was to determine the diffusion coefficients considering the hydrodynamic model for cubical configuration and evaluate the influence of vacuum pulse time and sucrose solution concentration on mass transfer kinetics (water loss and solid gain) and mechanical properties (stress at rupture) of melon cubes subjected to pulsed vacuum osmotic dehydration.

Material and methods

Raw material

Ripe melons (*Cucumis melo* L.) of the *Cucumis melo inodorus* variety, purchased at a local market (CEASA – Campinas – Brazil) one day before the osmotic process, were selected based on their ripeness level (9–10 Brix) and colour of skin (intense yellow) and flesh (cream) to minimise differences in raw material. The fruits were stored at 15 °C and 80% relative humidity until they were processed.

Sample preparation and osmotic dehydration

Fruits were washed with tap water and dipped in a peracetic acid solution (80 mg L^{-1}) for 3 min (Ecolab Química Ltda., São Paulo, Brazil). Melons were manually peeled, the seeds were removed, and then the pulp was cut into 20-mm cubes.

Osmotic dehydration tests were carried out in a special equipment designed to work at atmospheric pressure and/or under vacuum. The equipment consisted of a jacketed stainless steel chamber connected to a thermostatic bath (model TE-184; Tecnal, Piracicaba, Brazil) to control the solution temperature. The osmotic solution was stirred by a controlled flow recirculation system, using a sanitary pump. A vacuum pump was linked to the vessel, and a pressure transmitter was used to control the operational conditions. A control panel, programmed for manual and automatic operation, was linked to a computer so as to record the vacuum pressure, flow conditions and temperature values during the process, as shown in Figure S1 (see Supporting Information online) (Vivanco-Pezantes, 2006).

Melon cubes were initially weighed and placed in a single layer on perforated stainless steel trays to allow the solution flow through the samples and immersed in sucrose solutions (40°Brix: $a_w = 0.966 \pm 0.001$; 50°Brix: $a_w = 0.939 \pm 0.001$ or 60 Brix: $a_w = 0.898 \pm 0.001$). The choice of this sugar as osmotic solute was based on its low cost, convenience and desirable flavour. At predetermined times (30, 60, 90, 120, 180 and 240 min), samples were removed from the solution, drained and blotted with absorbent paper to remove excess solution, before being weighed. The overall time used was chosen according to other osmotic dehydration studies (Amami *et al*., 2006; Lombard *et al*., 2008; Blanda *et al*., 2009). As sampling was done in triplicate, eighteen trays with five melon cubes in each one were used in the

experiments. The temperature of osmotic solution employed was 30 °C, based on a previous work with osmotic dehydration of melon (Ferrari & Hubinger, 2008), with a recirculation level of 2.5 $m^3\ h^{-1}$, condition established in a prior study, with the aim of neglecting external resistance to mass transfer in the equipment (Vivanco-Pezantes, 2006). The equipment used was a pilot-scale device with a minimum solution volume of 22 L, and thus, the mass product-to-mass solution ratio was about 1:35 to avoid significant medium dilution and subsequent driving force decrease during the process. A vacuum pulse of 100 mbar was applied for the first 5, 10 or 15 min of osmotic dehydration, followed by the atmospheric pressure operation, which is in accordance with some similar works, such as Ito *et al.* (2007), Corrêa *et al.* (2010) and Escriche *et al.* (2002), because most of the studies with PVOD process have been carried out using short vacuum application times (5–15 min) and lower vacuum pressure (50–150 mbar).

Water loss and solid gain determinations

The moisture and solid contents of osmodehydrated melon cubes were evaluated throughout the process according to AOAC (2006) to determine water loss (WL) and solid gain (SG) according to Eqs. (1) and (2). Measurements were taken in triplicate.

$$\mathrm{WL}(\%) = 100.(w_0.X_{\mathrm{wb0}} - w_{\mathrm{f}}.X_{\mathrm{wbf}})/w_0 \qquad (1)$$

where w_0 is the initial sample mass (g); w_f is the final sample mass (g); X_{wb0} (%) is the initial moisture content (wet basis); and X_{wbf} (%) is the final moisture content (wet basis).

$$\mathrm{SG}(\%) = 100.(TS_{\mathrm{f}}.w_{\mathrm{f}} - TS_0.w_0)/w_0 \qquad (2)$$

where TS_0 and TS_f are the initial and final total solid contents (%), respectively.

Mathematical modelling

The estimation of diffusion coefficients was done using the hydrodynamic model for pulsed vacuum osmotic dehydration. In the kinetic studies of foods with high moisture content, such as fruits, a simplification in the equilibrium approach can be used (Fito & Chiralt, 1997):

$$z_{\mathrm{eq}}^{\mathrm{SS}} = y_{\mathrm{eq}}^{\mathrm{SS}} \qquad (3)$$

where z_{eq}^{SS} is the mass fraction of soluble solids in food liquid phase (g g^{-1}) and y_{eq}^{SS} is the mass fraction of soluble solids in osmotic solution (g g^{-1}), both at the equilibrium state. Therefore, the effective diffusivity (or pseudo-diffusivity) is the same for water and solids, and the following relation can be established:

$$D_{\mathrm{eff\,W\ or\ S}} = D_{\mathrm{eff_W}} = D_{\mathrm{eff_S}} \qquad (4)$$

The fruit liquid phase (FLP) composition is calculated by eqns 5 and 6.

$$z^{\mathrm{W}} = \frac{x^{\mathrm{W}}}{x^{\mathrm{W}} + x^{\mathrm{SS}}} \qquad (5)$$

$$z^{\mathrm{SS}} = \frac{x^{\mathrm{SS}}}{x^{\mathrm{W}} + x^{\mathrm{SS}}} \qquad (6)$$

where x^W is the mass fraction of water in food (g g^{-1}), x^{SS} is the mass fraction of soluble solids in food (g g^{-1}), z^W is the mass fraction of water in food liquid phase (g g^{-1}) and z^{SS} is the mass fraction of soluble solids in food liquid phase (g g^{-1}).

As the composition in the FLP can be considered a binary system, composed by water and solutes, the reduced driving force in food liquid phase, Y, is defined according to eqn 7:

$$Y = Y_t^{\mathrm{W}} = Y_t^{\mathrm{SS}} = \frac{z_t^{\mathrm{W}} - z_{\mathrm{eq}}^{\mathrm{W}}}{z_0^{\mathrm{W}} - z_{\mathrm{eq}}^{\mathrm{W}}} \qquad (7)$$

Fito & Chiralt (1997) assumed that the total transport of water and solids is caused by two main mechanisms:

1 the hydrodynamic mechanism that occurs at the beginning of process ($t = 0$ to $t = t_{HDM}$) and is dependent on the pressure gradients:

$$1 - Y_t^{\mathrm{W}}\big|_{t=0}^{t=t_{\mathrm{HDM}}} \cong K_1 \qquad (8)$$

2 a pseudo-Fickian mechanism which is driven by activity gradients at longer times and can be calculated using a simplified solution of Fick's equation for semi-infinite slab and short time (Crank, 1975), considering a single term of the series:

$$1 - Y_t^{\mathrm{W}}\Big|_{t=t_{\mathrm{HDM}}}^{t=t} = 2\left(\frac{D_{\mathrm{eff}}\,t}{\pi L^2}\right)^{0.5} = K_2.t^{0.5} \qquad (9)$$

These two effects were coupled to consider the effect of the hydrodynamic and the pseudo-Fickian mechanisms, resulting in eqn 10. Parameters D_{eff}, K_1 and K_2 were obtained for each experiment from a linear fitting of the experimental $1 - Y_t^W$ vs. $t^{0.5}$.

$$1 - Y_t^{\mathrm{w}}\big|_{t=0}^{t=t} = K_1 + 2\left(\frac{D_{\mathrm{eff}}t}{\pi\,L^2}\right)^{0.5} = K_1 + K_2.t^{0.5} \qquad (10)$$

Rastogi & Raghavarao (2004) defined the Fourier number for a cube as $3D_{eff}t/L^2$, so Fito and Chiralt model for this geometry becomes as follows:

$$1 - Y_t^{\mathrm{w}}\big|_{t=0}^{t=t} = K_1 + 2\left(\frac{3\,D_{\mathrm{eff}}t}{\pi\,L^2}\right)^{0.5} \qquad (11)$$

The criterion used to evaluate the best fit to the model was the estimative standard error (SE) (eqn 12) and the correlation coefficient R^2.

$$SE = \sqrt{\frac{\sum_{i=1}^{n} (OBS - PRED)^2}{n}} \quad (12)$$

where OBS is correspondent to the observed value of water or solid mass and PRED is the predicted value of water or solid mass. The term n corresponds to the number of observations. Effective diffusivities were determined using the non-linear estimation from software STATISTICA®5.0 (StatSoft Inc., Tulsa, OK, USA).

Mechanical properties: stress at rupture

Mechanical properties were analysed by uniaxial compression tests with a Universal Testing Machine (TA.TX Plus Texture Analyser; Stable Micro Systems, Surrey, England). Measurements were taken in quintuplicate using a 60-mm-diameter cylindrical acrylic probe, which was lubricated to avoid the effects of the plate–sample friction during compression. The stress-at-rupture tests were performed at a compression speed of 1 mm s^{-1} and 80% sample deformation (Rodrigues *et al*., 2006). The stress at rupture of each sample was determined from the peak of the stress–strain curve as follows:

$$\sigma_H = F(t)/A(t) \quad (13)$$

where $F(t)$ and $A(t)$ represent the compression force (N) and contact area of the sample with the probe (m^2) at each time t, respectively.

Contact area at each time t during the compression test was obtained from the measured area of melon cube sample before compression (A_0), the initial height (H_0) and the height at each time t, H(t), assuming constancy of sample volume during compression, according to eqn 14 (Mayor *et al*., 2007).

$$A(t) = A_0 H_0 / H(t) \quad (14)$$

Because the texture of fruits is not uniform, the results for each treatment were normalised as the ratio between the values for treated and fresh samples, to minimise the biological variability of different melon batches used during the experiments.

Statistical analysis

All the results were statistically analysed using the analysis of variance (ANOVA) with the software STATISTICA® 5.0 (StatSoft Inc.). Mean separation was performed using the Tukey test procedure at $P \leq 0.05$.

Results and discussion

Water loss and solid gain

Water loss and solid gain kinetics of melon cubes subjected to PVOD are presented in Figures S2 and S3, respectively. Higher sucrose solution concentrations provided an enhancement of water loss (Figure S2c) for all the conditions evaluated (vacuum pulse time of 5, 10 or 15 min). Similar trends were also reported in the osmotic dehydration of guava (Corrêa *et al*., 2010), mango (Ito *et al*., 2007; Torres *et al*., 2007) and pineapple (Lombard *et al*., 2008). Besides, all the samples showed a greater water loss from the fruit tissue during the first 2 h, as a consequence of the higher process driving force between the fruit and the hypertonic solution at the beginning of osmotic dehydration (Figure S2a,b,c). For treatments performed using 40°Brix, a gradual stabilisation of water loss was observed after 4 h (Figure S2a).

Concerning the influence of vacuum pulse time on water loss, no significant differences ($P \leq 0.05$) were observed in samples treated with 40, 50 or 60°Brix sucrose solutions. These results imply that solution concentration showed a greater influence than vacuum pulse time on water loss kinetics of osmodehydrated melon cubes. A similar behaviour was also verified by Escriche *et al*. (2002) and Ito *et al*. (2007) in their studies with kiwifruit and mango subjected to PVOD process, respectively.

With respect to solid gain, lower solid uptake was verified in osmodehydrated samples with 60°Brix sucrose solution (Figure S3c), probably because of the formation of a superficial solute layer around the fruits treated with more concentrated solutions, hindering solute uptake into the food, as previously noticed by Ferrari & Hubinger (2008). Barat *et al*. (2001) reported that the use of more concentrated osmotic solutions during PVOD process may play an important role in the reduction in HDM effect, which could reduce the solid gain throughout the process time, as observed for osmotic treatments with 60°Brix in this present work. The authors attributed this fact to a lower vacuum impregnation degree, caused by the cell structure collapse, when working at high osmotic solution concentration and/or temperature, which promotes a partial expulsion of osmotic solution with the release of internal gas, resulting in pores' shrinkage and the reduction in free volume available for impregnation. In accordance with Torres *et al*. (2007), low-viscosity (less concentrated) solutions combined with the vacuum pulse application at the beginning of osmotic process favours the hydrodynamic solution gain into the tissue pores, promoting an effective sample impregnation with lower water and mass loss. These results are also in agreement with those previously found out by Ito *et al*. (2007) and Corrêa *et al*. (2010) in their works with mangoes and guavas, respectively.

Vacuum time only had a significant effect ($P \leq 0.05$) on solid gain for osmodehydrated samples with 40°Brix sucrose solution (Figure S3a). Applying the vacuum pulse of 5 min resulted in lower solid incorporation in

the end of osmotic process (≅ 9%), when compared to the results obtained for vacuum pulses of 10 or 15 min (≅ 13%). This fact can be related to the lower viscosity of 40°Brix sucrose solution, allied to the action of hydrodynamic mechanism of PVOD, that is, the increase in vacuum time was able to promote an elevated sample degasifying, allowing a higher penetration of external solution into the food porous structure. Paes *et al.* (2007) have reported a similar trend in the osmotic dehydration of apples cylinders, using 50°Brix sucrose solution and vacuum pulses of 10–40 min. The authors observed an increase in sugar gain up to 25 min of vacuum time, reaching values around 22%, followed by a decrease in these results for longer vacuum impregnation time. According to Mújica-Paz *et al.* (2003), such decrease indicates that applying high vacuum pressure and/or long vacuum time may cause irreversible deformation of porous structure, leading to a reduction in free volume available for impregnation.

Distinct behaviours were noticed for solid gain curves of osmotic treatments performed with 40, 50 or 60°Brix sucrose solutions. Solid incorporation of osmodehydrated samples using 60°Brix (Figure S3c) remained practically unchanged after two hours of osmotic process. For treatments performed using 40°Brix sucrose solution, a significant increase ($P \leq 0.05$) in solid gain was verified in the end of osmotic process for samples subjected to a vacuum pulse for 10 or 15 min, in comparison with the results obtained for 5 min (Figure S3a). This fact could be associated with the effect of vacuum pulse application allied to the use of less concentrated sucrose solutions during the osmotic dehydration, allowing a higher uptake of osmotic solution into the pores, as already discussed in this section. However, at pulse time of 15 min, samples showed a fast solid incorporation in the first 30 min of osmotic process, which can be explained by the greater HDM effect at the beginning of PVOD process, performed with lower sucrose solution concentration and longer vacuum pulse time. Then, a stabilisation of solid uptake was noticed up to 180 min, followed by a significant increase in solid gain until the end of osmotic process (Figure S3a). It is possible that at 180 min, a rupture of cell wall may have occurred, resulting in higher solid incorporation. According to Fito *et al.* (1996), HDM mechanism is accompanied by food matrix deformation, which influences the final liquid uptake and affects the mechanical properties of the product after osmotic treatment, as a result of expansion and compression of the gas occluded into the fruit porous structure. Paes *et al.* (2007) observed a great increase in apple soluble solid content at the beginning of PVOD process, using an isotonic solution of 21.8°Brix, and the authors attributed this behaviour to the higher influence of HDM in the first 5 min of the relaxation period.

Comparing water loss and solid gain values obtained in this work with those of a previous study performed at atmospheric pressure (Ferrari & Hubinger, 2008), osmodehydrated samples at atmospheric pressure (OD), using 40 and 60°Brix sucrose solution, showed water loss values around 23 and 40%, respectively, after four process hours. Water loss results for the fruits subjected to PVOD ranged from approximately 28 to 29.5% (Figure S2a) and from 39 to 44% (Figure S2c) for treatments performed with sucrose solution at 40 and 60°Brix, respectively. Regarding the solid uptake, PVOD samples presented higher values in the end of process (Figure S3a,c), when compared to the results at atmospheric pressure (≅ 8 and 4% for 40 and 60°Brix sucrose solution, respectively). Higher water loss values observed in PVOD process with 40°Brix sucrose solution when compared to OD process can be explained by the coupled action of two different mechanisms (osmodiffusive and hydrodynamic) that occur during PVOD process, increasing mass transfer rates (Fito & Chiralt, 1997). Similar to the effect seen in water loss results, the combined action of these two mechanisms promoted the filling of sample pores with the external solution, resulting in a fast solid incorporation into the fruit tissue, as already reported by Blanda *et al.* (2009), Torres *et al.* (2007) and Lombard *et al.* (2008). However, in the present work, no significant differences were found out for water loss of samples treated with 60°Brix sucrose solution, in comparison with the results at atmospheric pressure. This could be attributed to high and fast solid gain observed in PVOD treatments, which makes the water diffusion from the solution to the fruit more difficult. Another aspect that could contribute in this sense is the higher solution viscosity at 60°Brix, creating a barrier and a resistance to water mass transfer.

Effective diffusivity

Table S1 shows the effective diffusivities determined by the hydrodynamic model (Fito & Chiralt, 1997). The effective diffusivity for both water and solids ranged from 1.261×10^{-9} to 1.601×10^{-9} $m^2 s^{-1}$, presenting correlation coefficients (R^2) between 0.931 and 0.971. The model also showed estimative SE lower than 0.08 for all conditions studied, demonstrating a good fit to the experimental data. The diffusivity values obtained in this work are in agreement with other studies (Amami *et al.*, 2006; Ito *et al.*, 2007; Matusek *et al.*, 2008).

K_1 and K_2 kinetic constants (Table S1) represent the contribution of the hydrodynamic and pseudo-diffusive mechanisms to the total mass changes, respectively, from fitting the experimental results to eqn 10. Mass transfer occurred by diffusive mechanisms is proportional to the square root of time in short process times, according to the integrated Fick's equation for short times, simplified to only one term of the series (eqn 9). Therefore, the slopes of each fitted line (K_2) are

associated with mass transfer rates of water and solutes occurred through diffusive/osmotic mechanisms in the tissue intercellular spaces, whilst the intercepts of each fitted line (K_1) quantify mass gain or losses at very short process times, owing to the action of HDM, promoted by imposed or capillary pressures (Fito & Chiralt, 1997). Moreover, because the vacuum effect depends on porous structure of vegetable tissue and sugar gain is closely related to this parameter, K_1 values can also be associated with the fruit porosity, that is, lower porosity values result in a poor contribution of hydrodynamic mechanism to the total mass transfer (lower K_1 values). In this context, the possible differences observed in the mass transfer kinetics during PVOD process can be explained by the differences in biological structural characteristics of the fruits studied (Escriche *et al*., 2000; Corrêa *et al*., 2010).

Positive values of K_1 ranging from 0.086 to 0.112 were obtained for all the conditions studied, but they were not affected by solution concentration or vacuum pulse time at $P \leq 0.05$. In a similar work, Corzo & Bracho (2007) reported that K_1 values of sardine sheets subjected to PVOD process were not influenced by brine concentration (0.15–0.27 g NaCl g^{-1}), but increasing the temperature (from 30 to 38 °C) caused a significant reduction in K_1 values, diminishing the effect of hydrodynamic mechanism on mass transfer rates. Evaluating the effect of temperature (30–50 °C) in the osmotic dehydration of guavas using 65°Brix sucrose solution and 5 min of vacuum pulse, Panadés *et al*. (2008) noticed positive values of K_1 constant at 30 and 40 °C, whilst at 50 °C, negative values of this parameter were observed. According to Barat *et al*. (2001), the action of hydrodynamic and capillary mechanisms may decrease at high osmotic solution concentration and/or temperature, resulting in a lower vacuum impregnation degree and consequently reducing the osmotic solution gain, which could explain the negative values of K_1 parameter. However, this behaviour was not verified in the present work, because solution concentration did not show a significant effect in K_1 results, as already discussed.

Higher K_2 values resulted in an increase in effective diffusivity. Despite greater water loss observed during treatments performed with higher sucrose solution concentration (Figure S2a,b,c), no statistical differences ($P \leq 0.05$) were found out amongst K_2 parameter or effective diffusivity values. In another work, Corrêa *et al*. (2010) observed higher effective diffusivity as solution concentration decreased for osmotically dehydrated guavas, whilst the vacuum pulse time also did not show a very clear tendency. Furthermore, the authors verified that the hydrodynamic model demonstrated a better agreement to the experimental data in comparison with the diffusive model, owing to the coupled effect of hydrodynamic mechanism and Fick's diffusion law considered in this mathematical model.

Mechanical properties: stress at rupture

The normalised stress-at-rupture values throughout the pulsed vacuum osmotic dehydration of melon cubes are shown in Figure S4. In spite of the heterogeneity amongst the fruits and the lack of internal structure uniformity in these biological materials (Ferrari & Hubinger, 2008), small deviations in the stress-at-rupture measurements were observed in all the conditions studied.

A significant effect of vacuum time ($P \leq 0.05$) on melon mechanical properties was only verified for the osmotic treatments carried out using 40°Brix sucrose solution (Figure S4a). Fresh fruit hardness was practically maintained up to 90 min of osmotic process, followed by a statistically significant decrease in stress-at-rupture values, when working with 5 min of vacuum pulse. On the other hand, the vacuum pulse application for 10 or 15 min caused a more pronounced reduction in stress at rupture, oscillating around 0.35 and 0.57 (Pa/Pa). A remarkable decrease in this parameter values was also observed for osmodehydrated fruits using 50°Brix sucrose solution (about 40–50%) (Figure S4b), whilst melon samples treated with 60°Brix showed lower stress-at-rupture results at the beginning of process, reaching values closer to fresh fruit after 120 min (Figure S4c). Hence, because vacuum promotes an opening of the pores, which makes the mass transfer easier and may change the fruit cellular structure, it is possible that vacuum pulse caused some mechanical damages in cell arrangement, such as cell turgor loss and alterations of cell wall resistance, because of the higher solids impregnation observed for treatments at 40°Brix (when vacuum pulse is applied for 10 or 15 min) and 50°Brix, contributing to the reduction in stress-at-rupture values. Similar trends in mechanical property changes were reported in studies with mangoes (Torres *et al*., 2008), strawberries (Castelló *et al*., 2010) and kiwifruit (Chiralt & Talens, 2005). In another work, Paes *et al*. (2006) attributed the reduction in maximum stress of apples subjected to osmotic process under vacuum (pressure of 40 mbar during 15 min) to the loss of cell turgor as sucrose solution concentration increased from 40 to 50°Brix.

Working with grapefruit, Moraga *et al*. (2009) concluded that PVOD treatments promoted a significant increase in all the mechanical parameters analysed, probably because to the structure of this kind of tissue. Grapefruit pulp is formed by segments with long cells containing the juice, and part of it is lixiviated during the cutting process of the samples. This fact can be responsible for its different mechanical response compared to the parenchymatic tissue of other fruits, such as mango, melon, kiwifruit and strawberry. Deng & Zhao (2008) and Allali *et al*. (2010) also verified higher firmness values for apple samples subjected to PVOD

(pressure of 100 mbar during 5 min), and they attributed this fact to the replacement of the gas occluded into the pores by the osmotic solution, obtaining a more compact structure. According to Mújica-Paz *et al.* (2003), fruits as apple show higher porosity values and their response to vacuum application is linear, which means that its solid matrix suffers minor deformation and smaller collapse of tissue structure, owing to the pressure changes. Nevertheless, when increasing vacuum pressure or time, the structure of mango, peach and melon presents higher deformation levels, which contributes to the alterations in their mechanical properties.

Conclusions

Osmotic solution concentration showed a greater influence than the vacuum pulse application on mass transfer kinetics of osmodehydrated melon cubes. The increase in sucrose solution concentration favoured water removal, but a significant effect of vacuum pulse time on water loss was not observed. The use of lower-viscosity solutions combined with the action of vacuum pulse at the beginning of process promoted greater solid uptake, which decreased as solution concentration increased. The stress at rupture was affected by mass transfer throughout processing, as well as by solution concentration and vacuum pulse time. A significant reduction in stress at rupture in comparison with fresh fruit values was noticed for treatments performed with 40°Brix and 50°Brix sucrose solutions. Osmodehydrated samples in 60°Brix sucrose solution presented a better preservation of fresh fruit texture characteristics all along the treatment time. The effective diffusivity for both water and solids estimated by the hydrodynamic model varied between 1.261×10^{-9} and 1.601×10^{-9} m^2 s^{-1}. A good fit to the experimental data was obtained, with correlation coefficients (R^2) values higher than 0.931 and estimative SE lower than 0.08, which indicates that the coupled effect of hydrodynamic mechanism and Fick's diffusion law considered in this mathematical model was effective for the modelling of mass transfer phenomena during pulsed vacuum osmotic dehydration.

In a general way, treatments performed with 60°Brix sucrose solution can be considered the best conditions obtained in this work, because samples subjected to PVOD process using more concentrated osmotic solutions with the vacuum pulse application for 5, 10 or 15 min at the beginning of osmotic dehydration showed greater water loss, lower sugar uptake and a higher maintenance of fresh fruit texture throughout the process.

Acknowledgments

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Scheme of equipment designed to work at atmospheric pressure and/or under vacuum.

Figure S2. Water loss kinetics of melon cubes subjected to pulsed vacuum osmotic dehydration (PVOD) using sucrose solution at (a) 40°Brix, (b) 50°Brix and (c) 60°Brix and applying a vacuum pulse of 100 mbar during 5, 10 or 15 min.

Figure S3. Solid gain kinetics of melon cubes subjected to pulsed vacuum osmotic dehydration (PVOD) using sucrose solution at (a) 40°Brix, (b) 50°Brix and (c) 60°Brix and applying a vacuum pulse of 100 mbar during 5, 10 or 15 min.

Figure S4. Normalised stress-at-rupture kinetics of melon cubes subjected to pulsed vacuum osmotic dehydration (PVOD) using sucrose solution at (a) 40°Brix, (b) 50°Brix and (c) 60°Brix and applying a vacuum pulse of 100 mbar during 5, 10 or 15 min.

Table S1. Effective diffusivities for water and solids determined based on Fito & Chiralt (1997) hydrodynamic model

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