Osmotic dehydration with sorbitol combined with hot air convective drying of apple cubes

Fernanda R. Assis¹ · Rui M. S. C. Morais¹ · Alcina M. M. B. Morais¹

Revised: 7 June 2017 / Accepted: 7 July 2017 / Published online: 17 July 2017
© Association of Food Scientists & Technologists (India) 2017

Abstract The aim of the present work was to study the effect of the osmotic dehydration (OD) pre-treatment on the mass transfer kinetics and water activity (a_w) of apple cubes during hot air drying. The adequacy of different mathematical models to describe the moisture content of the product during this process was also evaluated. Apple cubes were osmotically dehydrated with sucrose or sorbitol solutions at 60 °C, and then dried by air at 25–80 °C. Overall, the OD and rise of the air temperature resulted in an increased water loss rate and a reduction of the a_w . The osmotic agent used in the OD was not relevant to the air drying kinetics, but the pre-treatment with sorbitol solutions produced dried samples with lower a_w . Newton's, Page's, modified Page's, Henderson and Pabis', Two-term, Two-term exponential, Logarithmic, Midilli et al.'s models could describe the moisture content well during the air drying process.

Keywords Apple cubes · Osmotic dehydration · Hot air drying · Mass transfer · Mathematical models

List of symbols

a Half of the side of the cube (m)
 a_w Water activity
 A, B Page's and Modified Page's models parameters

a, k Henderson and Pabis' and Two-term exponential models parameters
 a, k_1, k_2 Two-term model parameters
 a, k, c Logarithmic model parameters
 a, b Wang and Singh's model parameters
 a, k, n, b Midilli et al.'s model parameters
 a, k, b, B Weibull's model parameters
 c, k GAB's model constants
 D_e Effective diffusivity ($\text{m}^2 \text{s}^{-1}$)
 E_a Activation energy (J mol^{-1})
 k Newton's model parameter
 M Moisture content ($\text{kg water kg dry matter}^{-1}$)
 M_m Monolayer moisture content ($\text{kg water kg dry matter}^{-1}$)
 M_0 Initial moisture content ($\text{kg water kg dry matter}^{-1}$)
 M_∞ Moisture content at equilibrium ($\text{kg water kg dry matter}^{-1}$)
OD Osmotic dehydration
 p Arrhenius's parameter
 p_{ref} Arrhenius's parameter at the reference temperature
 R Universal gas constant ($\text{J mol}^{-1} \text{K}^{-1}$)
 T Temperature (°C, K)
 t Time (s)
 w_0 Initial weight of the sample (kg)

Introduction

The dehydration consists of reducing the water content of the food, decreasing the water activity (a_w), thereby, inhibiting the growth of microorganisms and delaying the deterioration of physico-chemical origin (Cano-Chauca et al. 2004). The hot air dehydration is very common in the

✉ Alcina M. M. B. Morais
abmorais@porto.ucp.pt

¹ CBQF - Centro de Biotecnologia e Química Fina –
Laboratório Associado, Escola Superior de Biotecnologia,
Rua Arquiteto Lobão Vital, Universidade Católica
Portuguesa, Apartado 2511, 4202-401 Porto, Portugal

food industry due to being considered an economical method to produce dehydrated products from higher initial moisture content, and also to involve easy operated drying equipment (Kaur et al. 2014; Kowalski and Szadzińska 2014). The osmotic dehydration (OD), consisting of the immersion of foods in aqueous solutions of high osmotic pressure for the partial removal of water, can produce intermediate moisture food, but the moisture content and water activity levels reached are not enough to obtain shelf stable products. Thus, OD is often used as pre-treatment before other drying process, also reducing the time of the subsequent process (Khan 2012).

The use of OD previous to convective drying may be used in order to improve the rehydration characteristics, texture and colour of the final products (Kaur et al. 2014). Velickova et al. (2014) evaluated the physical and sensory properties of apples chips produced by OD followed by convective drying. This product presented acceptable colour, mechanical properties and good acceptability by the consumers. Kowalski and Mierzwa (2013) examined the influence of OD on the convective drying of apples and they found that the OD improved the quality of dried product, but did not affect the drying rate. Araya-Farias et al. (2014) studied the vacuum and hot-air drying kinetics of seabuckthorn berries osmotically dehydrated and noted that the moisture content of air-dried samples decreased more than the vacuum dried ones. Fernandes et al. (2006a) optimized the OD process followed by air drying of banana and they concluded that the osmotic pre-treatment with higher solute concentrations reduced the total processing time.

To describe the mass transfer kinetics of the drying process, mathematical models (empirical, semi-empirical and phenomenological) may be used to fit the experimental data. The phenomenological model more used is based on the Fick's second law, but it is applied only for classical geometries. This model was able to determine the diffusion coefficient of several types of drying process of papaya, green peas and lemon waste (Garcia et al. 2014; Puente-Díaz et al. 2013; Zielinska et al. 2013). The empirical and semi-empirical models can be applied to non-classical geometries, but they do not take into account the phenomenological mechanisms in the drying process. Some of these models are Newton's, Page's, modified Page's, Henderson and Pabis', Two-term, Two-term exponential, Verma et al.'s, Logarithmic, Wang and Singh's, Midilli et al.'s and Weibull's distribution. According to Lopes de Menezes et al. (2013), the Page's model was the best to describe the experimental data of convective drying of pomace of yellow passion fruit. The logarithmic and Midilli et al.'s models could predict the moisture content during air drying of coroba slices in a study performed by Corzo et al. (2010). Hui et al. (2011) found that the two-term model presented a good fit to the experimental

data of hot air drying of litchi pulp. For pepper dried in an air impingement dryer, Qian et al. (2011) found that the modified Page's model was suitable to fit the experimental data.

The objectives of this work were: i) to carry out the osmotic dehydration of apple cubes (variety Royal Gala) at 60 °C, using two solutes—sucrose or sorbitol—at a mass ratio sample/solution of 1:4 (based on a previous study, Assis et al. 2016), followed by hot air drying, and to study the effect of the air temperature from 25 to 80 °C on the mass transfer kinetics and on the water activity of the product; ii) to test the adequacy of the fitness of some empirical, semi-empirical and phenomenological mathematical models to describe the moisture content of the product during the hot air drying.

Materials and methods

Samples

Apples (*Malus* spp., variety Royal Gala) were graciously supplied by Campotec, Portugal, and stored at 4 °C. The fruits were washed and sanitized with aqueous solution with 7500 ppm active chlorine for 5 min. Then, the samples were cut in cubes (12 × 12 × 12 mm) with a vegetable cutter (Secret de Gourmet, JJA, Le Blanc Mesnil, France) and immersed in a solution with 0.9% sodium chloride for 3 min to prevent enzymatic browning. The samples were blotted gently with a tissue paper in order to remove the excess of sodium chloride solution from the surface. The soluble solids content of the apple was 14.8 ± 0.6 °Brix (hand refractometer, Atago, U.S.A., Inc., WA, USA).

Osmotic dehydration

The apple samples were immersed in the osmotic solution with sucrose or sorbitol at 60° Brix for 8 h at 60 °C at the atmospheric pressure. The mass ratio of sample to solution used was 1:4. The OD was carried out at constant temperature and agitation (50 rpm). Then, the samples were rinsed with ultra-pure water to remove the solution adhered to the surface and blotted with tissue paper to remove the excess of water from the surface.

Hot air drying

The hot air drying experiments were performed in an oven (UFP800DW, Memmert, Germany) with recirculation of air. The air velocity was measured with an anemometer (Airflow LCA 6000, England) and it was fixed at approximately 1 m s^{-1} . The relative humidity was measured with

a hygroLog (HL-NT2, Rotronic, Switzerland) during the process.

Around 150 g of control (fresh) samples or 50 g of osmotically dehydrated samples were used in each drying experiment. The drying experiments were carried out at 25, 55, 70 and 80 °C. The longest drying time was 10 h at 25 °C. Each drying experiment was carried out twice and the experimental data were duplicated.

Moisture content determination

The moisture content was determined in samples of around 5 g at given times during the drying experiments. It was determined in an oven (FP115, Binder, Tuttlingen, Germany) at 105 °C until constant weight (A.O.A.C. 2002).

The determinations were performed in duplicate.

Water activity determination

The water activity of the samples was determined during the drying process at specific times. The a_w of the samples was determined with a hygrometer (Aqualab Series 3, Decagon Devices Inc., Pullman, Washington, USA) at 22 °C.

The determinations were performed in duplicate.

Mathematical models

The moisture ratio (MR) of the samples was used to describe the experimental data during the drying process:

$$MR = \frac{M - M_{\infty}}{M_0 - M_{\infty}} \quad (1)$$

M_0 is the initial moisture content, M is the moisture content at time t , and M_{∞} is the moisture content at equilibrium, all in dry basis ($\text{kg}_{\text{water}} \text{kg}_{\text{dry matter}}^{-1}$). All M_{∞} -values were predicted by the models.

With the aim to describe the moisture loss of the osmotically dehydrated apple cubes during the hot air drying, some mathematical models, phenomenological and empirical or semi-empirical, were used to fit the experimental data. The model's equations will be described below:

Newton

$$MR = \exp(-k \cdot t) \quad (2)$$

Page

$$MR = \exp(-A \cdot t^B) \quad (3)$$

Modified Page

$$MR = \exp(-(A \cdot t)^B) \quad (4)$$

Henderson and Pabis

$$MR = a \cdot \exp(-k \cdot t) \quad (5)$$

Two-term

$$MR = a \cdot \exp(-k_1 \cdot t) + b \cdot \exp(-k_2 \cdot t) \quad (6)$$

Two-term exponential

$$MR = a \cdot \exp(-k \cdot t) + (1 - a) \cdot \exp(-k \cdot a \cdot t) \quad (7)$$

Logarithmic

$$MR = a \cdot \exp(-k \cdot t) + c \quad (8)$$

Midilli et al.

$$MR = a \cdot \exp(-k \cdot t^n) + b \cdot t \quad (9)$$

Weibull

$$MR = a - b \cdot \exp(-(k \cdot t^B)) \quad (10)$$

Wang and Singh

$$MR = 1 + a \cdot t + b \cdot t^2 \quad (11)$$

Crank

$$MR = \left[\sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \cdot \pi^2} \exp\left(-\frac{(2n+1)^2 \cdot \pi^2 \cdot De \cdot t}{4a^2}\right) \right]^3 \quad (12)$$

The relation between the equilibrium moisture content and the water activity of the dried apple cubes was predicted using Guggenheim-Anderson-de Boer (GAB) model. This model is reported to be the best for fitting sorption isothermal data for the majority of food products (Barbosa-Cánovas and Vega-Mercado 1996). The GAB model is expressed as:

$$\frac{M_{\infty}}{M_m} = \frac{c \cdot k \cdot a_w}{(1 - k \cdot a_w) \cdot (1 - k \cdot a_w + c \cdot k \cdot a_w)} \quad (13)$$

c and k are constants and M_m is described as the monolayer moisture content on dry basis ($\text{kg}_{\text{water}} \text{kg}_{\text{dry matter}}^{-1}$).

The Arrhenius behaviour

The linearized Arrhenius equation gives the dependence of the parameter p of the models on the temperature:

$$\ln p = \ln p_{ref} + \frac{E_a}{R \cdot T_{ref}} - \frac{E_a}{R} \cdot \frac{1}{T} \quad (14)$$

p is the parameter; p_{ref} is the parameter at the reference temperature; E_a is the activation energy (kJ mol^{-1}); R the universal gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$); and T and T_{ref} are the temperature used and the reference temperature (K), respectively. $T_{ref} = 298.15 \text{ K}$ was used in this work.

Statistical analysis

The statistical analysis was performed using Microsoft Excel 2000 (Microsoft Corporation, USA) (mean and standard deviation calculations) and IBM SPSS® Statistics 20.0 for Windows® (2012, SPSS Inc., Chicago, USA). The mathematical models mentioned above were fitted to the experimental data obtained at the different conditions tested. The model parameters were estimated by non-linear regression procedures, and the margin of error of the estimates was calculated at 95%. The regressions were also assessed by ANOVA approaches and the significance level assumed was 5%.

The adequacy of the models fit was evaluated by the determination coefficient (R^2) and by the residual analysis. The normality of the residuals was evaluated by Kolmogorov–Smirnov test.

Results and discussion

First, air drying experiments were carried out with fresh samples (control) and samples osmotically dehydrated with the sucrose solution at temperatures from 25 to 80 °C.

Fig. 1 Experimental data and the fit of Page's model of the normalized moisture content (M/M_0) during the air drying of control apple cubes

Fig. 2 Experimental data and the fit of Page's model of the normalized moisture content (M/M_0) during the air drying of apple cubes osmotically dehydrated in sucrose solutions

Then, air drying experiments were performed with the osmotically dehydrated samples with the sorbitol solution at 25 and 80 °C. As no significant differences were observed in the water loss rate between the two osmotic agents used in the OD, the experiments with the sorbitol solution at others temperatures (55 and 70 °C) were not carried out.

The moisture ratio of the apple cubes, fresh or osmotically dehydrated, dried at different air temperatures decreased with the drying time. Due the variability of the experimental data after the OD pre-treatment, the moisture content, M , was normalized to M/M_0 . Only the falling rate period was noticed for all conditions (Figs. 1, 2, 3). Araya-Farias et al. (2014), Garcia et al. (2014), Hemis and Raghavan (2014) and Yu et al. (2015) found the same in different types of drying of seabuckthorn fruit, papaya slices, soybean and hawthorn slices. Nieto et al. (2001) also did not detect the constant rate period during the air drying of blanched and/or osmotically dehydrated mango.

Mathematical modelling

The results of the non-linear regression of the experimental data of the hot air drying of the apple cubes are shown in

Fig. 3 Experimental data and the fit of Page's model of the normalized moisture content (M/M_0) during the air drying of apple cubes osmotically dehydrated in sorbitol solutions

Tables 1 and 2. The Newton's, Page's, Modified Page's, Midilli et al.'s, Henderson and Pabis', Two-term, Two-term exponential and Logarithmic models presented high values of determination coefficients (R^2) and the residual analysis showed that the residuals are normally distributed at the significance level of 5%; the visual analysis of the scatterplot of residuals versus predicted values allowed to observe that the residuals were distributed randomly around zero with no systematic patterns, satisfying the assumption of homoscedasticity and zero mean errors.

The k (Newton's, Henderson and Pabis', Midilli et al.'s and Logarithmic models) and A (Page's and Modified Page's models) parameters presented the same trend, in general, increasing with the air drying temperature (Tables 1 and 2). This tendency is in agreement with Puente-Díaz et al. (2013) and Qian et al. (2011), who used Newton's and Henderson and Pabis' models and the modified Page's model, respectively. Both these parameters can be related with the water diffusion rate (Kaur et al. 2014; Ruiz-López et al. 2010). Thus, the drying rate increased with the increase of temperature up to 70 °C, but at 80 °C no significant difference was observed in comparison with 70 °C. According to Simal et al. (1997), the air drying rates of apple cubes were similar at temperatures between 60 and 90 °C.

In general, the OD pre-treatment also influenced the air drying. The values of k parameter of Henderson and Pabis' model are higher for the osmotically dehydrated samples than the control samples. The solute used in the OD did not produce significant differences in this parameter. The A -values of the Page's model relative to the air drying of osmotically dehydrated samples are also higher than for the control samples, except for the osmotically dehydrated samples with sucrose solution at 80 °C (Table 1). According to Fernandes et al. (2006b), the convective drying rate of osmotically pre-treated papaya was higher than without the pre-treatment. Ruiz-López et al. (2010) also found an increase in A parameter of Page's model for osmotically pre-treated chayote slabs in comparison with

the fresh samples. Lenart and Cerkowniak (1996) studied the effect of different solutes (sucrose and starch) in the osmotic dehydration of apples and found that the osmotic solute did not affect the kinetics of the subsequent convective drying at 30 °C.

There was no clear tendency for some parameters of some models in relation to the different samples (osmotically dehydrated with different solutes and the control), such as k parameter of Newton's and a parameter of Henderson and Pabis' models (Table 1). In addition, the solute used in the OD did not have an influence on some other parameters: A and B of modified Page's model and A and B of Page's model at 25 and 80 °C.

The adequacy of Page's model was also observed by Yan and Jianwei (2012) during the hot air drying of schisandra. Assis et al. (2016) also found that this model was suitable as well to describe the experimental data of OD of apples cubes. As for the hot air drying, the A parameter also increased with the temperature of the OD process.

Both parameters of the two-term exponential model did not present a clear pattern. The parameters a , b and n of Midilli et al.'s model did not show differences either among the operation conditions or the samples (Table 2). The a -values are close to 1. This is in agreement with Corzo et al. (2010) and Kaur et al. (2014). The k parameter is higher for osmotically treated samples and higher temperatures, except at 80 °C. Corzo et al. (2010) also found that k increased with the temperature in hot air drying of coroba slices. Unal and Sacilik (2011) tested five models and concluded that Midilli et al.'s model presented an excellent fit of the experimental data of hawthorn fruits during the hot air drying.

The parameters of the two-term and the logarithmic models (data not shown) presented high values of margin of error, making them not significantly different among the different conditions used. However, this fact is not related with the quality of the fit model, since the R^2 values are between 0.961 and 0.998 and the residuals are random and

Table 1 Parameters of the fit of Newton's, Page's, modified Page's and Henderson and Pabis' models of the moisture ratio during air drying of apple cubes

Osmotic agent of previous OD	T- air drying (°C)	Models		Newton's			Page's			Modified Page's			Henderson and Pabis'		
		k ± margin of error	R ²	A ± margin of error	B ± margin of error	R ²	A ± margin of error	B ± margin of error	R ²	A ± margin of error	B ± margin of error	R ²	k ± margin of error	a ± margin of error	R ²
Sucrose	25	0.396 ± 0.035	0.985	0.398 ± 0.034	0.875 ± 0.076	0.987	0.349 ± 0.048	0.875 ± 0.076	0.987	0.349 ± 0.048	0.875 ± 0.076	0.987	0.362 ± 0.039	0.965 ± 0.025	0.987
Sorbitol	25	0.383 ± 0.052	0.986	0.441 ± 0.034	0.735 ± 0.071	0.997	0.328 ± 0.035	0.735 ± 0.071	0.997	0.328 ± 0.035	0.735 ± 0.071	0.997	0.363 ± 0.059	0.969 ± 0.057	0.987
Sucrose	55	0.673 ± 0.093	0.977	0.748 ± 0.071	1.343 ± 0.138	0.988	0.805 ± 0.062	1.343 ± 0.138	0.988	0.805 ± 0.062	1.343 ± 0.138	0.988	0.814 ± 0.091	1.095 ± 0.036	0.988
Sucrose	70	1.379 ± 0.091	0.994	1.503 ± 0.138	1.088 ± 0.078	0.995	1.454 ± 0.097	1.088 ± 0.078	0.995	1.454 ± 0.097	1.088 ± 0.078	0.995	1.454 ± 0.114	1.027 ± 0.027	0.995
Sucrose	80	1.469 ± 0.343	0.951	1.710 ± 0.713	1.123 ± 0.318	0.952	1.612 ± 0.429	1.123 ± 0.318	0.952	1.612 ± 0.429	1.123 ± 0.318	0.952	1.804 ± 0.417	1.106 ± 0.090	0.961
Sorbitol	80	1.989 ± 0.134	0.993	1.718 ± 0.246	0.892 ± 0.087	0.994	1.834 ± 0.205	0.892 ± 0.087	0.994	1.834 ± 0.205	0.892 ± 0.087	0.994	1.838 ± 0.150	0.959 ± 0.027	0.995
–	25	0.173 ± 0.034	0.980	0.144 ± 0.018	1.317 ± 0.138	0.989	0.230 ± 0.030	1.317 ± 0.138	0.989	0.230 ± 0.030	1.317 ± 0.138	0.989	0.181 ± 0.028	1.049 ± 0.020	0.990
–	55	0.630 ± 0.026	0.997	0.629 ± 0.023	1.059 ± 0.043	0.998	0.645 ± 0.027	1.059 ± 0.043	0.998	0.645 ± 0.027	1.059 ± 0.043	0.998	0.636 ± 0.032	1.010 ± 0.014	0.997
–	70	0.916 ± 0.116	0.986	0.954 ± 0.063	1.250 ± 0.069	0.997	0.963 ± 0.052	1.250 ± 0.069	0.997	0.963 ± 0.052	1.250 ± 0.069	0.997	0.901 ± 0.086	1.053 ± 0.024	0.995
–	80	1.036 ± 0.155	0.982	1.044 ± 0.130	1.179 ± 0.109	0.993	1.045 ± 0.106	1.213 ± 0.112	0.993	1.045 ± 0.106	1.213 ± 0.112	0.993	0.902 ± 0.128	1.028 ± 0.030	0.991

Table 2 Parameters of the fit of Two-term exponential and Midilli et al.'s models of the moisture ratio during air drying of apple cubes

Osmotic agent of OD	Temperature of air drying (°C)	Models		Two-term exponential			Midilli et al.'s		
		a ± margin of error	k ± margin of error	R ²	a ± margin of error	k ± margin of error	a ± margin of error	k ± margin of error	R ²
Sucrose	25	0.306 ± 0.179	0.819 ± 0.487	0.987	0.973 ± 0.043	0.397 ± 0.063	0.977 ± 0.163	–0.004 ± 0.008	0.988
Sorbitol	25	0.231 ± 0.283	1.168 ± 1.711	0.995	1.000 ± 0.033	0.487 ± 0.075	0.812 ± 0.149	–0.005 ± 0.007	0.997
Sucrose	55	1.952 ± 0.099	1.282 ± 0.133	0.989	1.053 ± 0.047	0.985 ± 0.180	0.353 ± 0.225	–0.040 ± 0.034	0.992
Sucrose	70	1.573 ± 0.168	1.831 ± 0.272	0.994	1.004 ± 0.036	2.073 ± 0.422	1.227 ± 0.157	–0.064 ± 0.038	0.996
Sucrose	80	1.645 ± 0.505	2.128 ± 1.063	0.952	1.116 ± 0.209	1.527 ± 3.165	0.886 ± 0.505	–0.020 ± 0.572	0.962
Sorbitol	80	0.353 ± 0.187	3.626 ± 1.854	0.994	0.967 ± 0.038	1.818 ± 1.001	0.955 ± 0.180	–0.013 ± 0.148	0.995
–	25	1.881 ± 0.095	0.346 ± 0.050	0.989	1.041 ± 0.051	0.192 ± 0.122	1.206 ± 0.388	–0.019 ± 0.134	0.991
–	55	1.515 ± 0.114	0.786 ± 0.076	0.998	0.994 ± 0.021	0.626 ± 0.090	1.078 ± 0.100	–0.001 ± 0.021	0.998
–	70	1.816 ± 0.068	1.399 ± 0.112	0.997	1.015 ± 0.027	1.112 ± 0.278	1.272 ± 0.167	–0.042 ± 0.076	0.997
–	80	1.721 ± 0.130	1.377 ± 0.220	0.993	1.001 ± 0.030	0.780 ± 0.819	1.115 ± 0.281	–0.069 ± 0.234	0.993

normally distributed. The k parameter of the logarithmic model increases with the air temperature, which is in agreement with Corzo et al. (2010).

However, all the models discussed above are empirical or semi-empirical and, therefore, they do not present any physical meaning. Crank's, Wang and Singh's and Weibull's models did not describe well the experimental data, as $R^2 < 0.9$ and the residuals are neither random nor normally distributed. Among the models tested, Crank's is the only phenomenological model, which would allow for a physical meaning.

The inadequacy of Crank's model was not expected, as this model uses theoretical basis adequate to the geometry of the product. The dimensions of the samples in the present work were not very different from the ones used in other works. Velić et al. (2004) studied the convective drying of rectangle-shaped ($20 \times 20 \times 5$ mm) apple samples; Sacilik and Elicin (2006) studied the drying of apple slices (5 and 9 mm). In both works the effective diffusivity was calculated using the solution of Fick's second law for slab. In fact, Crank's is the most used model, because it is a phenomenological one and is able to determine the effective diffusivity of the water, but in some studies the fit adequacy was not presented (An et al. 2013; Singh and Gupta 2007).

The Arrhenius's behaviour was observed for the k parameters of Newton's, Henderson and Pabis's, Midilli et al.'s and two-term exponential models and the A parameters of Page's and modified Page's. The linearity of the data ($R^2 > 0.90$) shows that these parameters were influenced by temperature. The activation energy (E_a) values of these parameters are between 15.27 ± 6.22 and 25.88 ± 8.19 kJ mol⁻¹ for samples osmotically dehydrated with sucrose, and between 23.49 ± 11.9 and 32.80 ± 17.03 kJ mol⁻¹ for the control samples during the air drying (data not shown). Higher E_a indicates a greater sensitivity of the parameter to temperature. However, no significant differences were found among the samples (osmotically dehydrated and control). The parameter p_{ref} did not present differences, except for k of the two-term exponential model: 0.794 ± 0.222 (OD) versus 0.347 ± 0.186 (control). No correlation could be found between the other parameters and the temperature in the experimental conditions used.

Water activity (a_w)

The a_w of the fresh apple cubes was 0.993 ± 0.003 and, after osmotic dehydration, it ranged from 0.851 to 0.949. The a_w of these samples subsequently dried by hot air decreased with the process time and, consequently, with the final water content. At the end of the process, the final a_w was between 0.245 and 0.493. The a_w of the hot air

dried samples previously osmotically dehydrated with the sorbitol solution presented lower values than with the sucrose solution, for the same drying time. This is an advantage because food with low water activity is less susceptible to oxidation and non-enzymatic browning.

The fact that the use of sorbitol as osmotic agent did not affect the water loss rate, in comparison with sucrose, but resulted in a lower water activity of the product may be explained by the results found before the air drying, i.e. the osmotically dehydrated samples with sorbitol solutions presented already lower values of a_w than the samples osmotically dehydrated with sucrose solutions. These results followed the same pattern of the initial rate of water loss and it was attributed to the lower viscosity of sorbitol solutions, as well as to their higher molar concentration, in comparison to sucrose solutions at the same mass concentration, 60 °Brix (Assis et al. 2016). This difference in the a_w of the samples osmotically dehydrated by the two solutes was reflected in the a_w values of the final air-dried product. Thus, after the same total air drying time at 80 °C, the reduction of the a_w was 68 and 74% for the osmotic pre-treatment with sucrose and the osmotic pre-treatment with sorbitol, respectively.

The drying time of the control samples was 10 and 2.9 h at 25 and 80 °C, respectively (Fig. 1). As expected, the OD pre-treatment reduced the air drying time, by 20%, using sucrose, and 30%, using sorbitol, for hot air drying at 25 °C. At 80 °C, the reduction was 22 and 39%, using sucrose and sorbitol as the osmotic agent, respectively. Therefore, the OD pre-treatment with sorbitol was more effective than sucrose in reducing the air drying time.

The GAB model fitted well the experimental data of moisture content versus a_w . The behaviour of the isotherms was different for the control and the pre-treated samples. For the control samples, the isotherms are close at the beginning of the drying process and they become separated in the end of the process. This behaviour is inverted for the osmotically dehydrated samples.

The GAB parameters (Table 3) did not follow the Arrhenius behaviour and no relation was observed between the process variables. The values of M_m ranged from 0.133 to 1.012 and were in agreement with Farahnaky et al. (2009) and Kaymak-Ertekin and Gedik (2004). The parameter M_m was higher for the control samples when compared with the osmotically dehydrated ones, except at 55 °C. However, no difference was observed in this parameter for the samples pre-treated with the two different solutes. This could be explained given that M_m is the amount of water that is strongly adsorbed to specific sites of the food surface, that cannot be removed by drying, and could be similar for the samples osmotically dried with both solutes (Bruijn and Bórquez 2014; Vega-Gálvez et al. 2014).

Table 3 GAB parameters and regression coefficients for isothermal desorption of osmotically dehydrated apple cubes

Osmotic agent of OD	Temperature of air drying (°C)	GAB model			R ²
		c ₁ ± margin of error	k ± margin of error	M _m (kg _{water} ·kg _{dry matter} ⁻¹) ± margin of error	
Sucrose	25	3.085 ± 4.922	0.934 ± 0.029	0.140 ± 0.040	0.975
Sorbitol	25	2.607 ± 2.161	0.863 ± 0.059	0.246 ± 0.081	0.988
Sucrose	55	1.678 ± 1.799	0.904 ± 0.031	0.209 ± 0.068	0.989
Sucrose	70	7.192 ± 13.356	0.950 ± 0.014	0.133 ± 0.024	0.993
Sucrose	80	2.995 ± 2.127	0.875 ± 0.035	0.183 ± 0.045	0.996
Sorbitol	80	2.573 ± 1.188	0.893 ± 0.027	0.222 ± 0.041	0.998
–	25	180.915 ± 14,098.6	0.943 ± 0.012	0.451 ± 0.081	0.983
–	55	0.210 ± 0.727	0.913 ± 0.104	1.012 ± 2.639	0.988
–	70	2.032 ± 5.629	0.957 ± 0.020	0.360 ± 0.149	0.987
–	80	1.911 ± 1.972	0.956 ± 0.007	0.376 ± 0.053	0.998

Conclusion

The osmotic dehydration pre-treatment had a significant influence on both the mass transfer kinetics of the air drying and the water activity of apple cubes at the conditions tested. The increase of the air temperature resulted in an increase of the drying rate and, consequently, the drying time was reduced. The hot air drying process decreased the water activity of the apple cubes significantly. The use of sorbitol as osmotic agent did not affect the water loss rate, in comparison with sucrose, but resulted in a lower water activity of the product.

Newton's, Page's, Modified Page's, Henderson and Pabis', Two-term, Two-term exponential, logarithmic, Midilli et al.'s models could describe the moisture ratio well during the hot air drying process.

Acknowledgements This work was supported by National Funds from FCT – Fundação para a Ciência e Tecnologia through project UID/Multi/50016/2013. The first author acknowledges the financial support of CAPES (1528/13-0). The authors also acknowledge Campotec for graciously supplying the apples for this study.

References

- An K, Li H, Zhao D, Ding S, Tao H, Wang Z (2013) Effect of osmotic dehydration with pulsed vacuum on hot-air drying kinetics and quality attributes of cherry tomatoes. *Dry Technol* 31:698–706
- A.O.A.C. (2002) Association of the Official Analytical Chemists - Official Methods of Analysis
- Araya-Farias M, Macaigne O, Ratti C (2014) On the development of osmotically dehydrated seabuckthorn fruits: pretreatments, osmotic dehydration, postdrying techniques, and nutritional quality. *Dry Technol* 32:813–819
- Assis FR, Morais RMSC, Morais AMMB (2016) Mathematical modelling of osmotic dehydration kinetics of apple cubes. *J Food Process Preserv*. doi:10.1111/jfpp.12895
- Barbosa-Cánovas GV, Vega-Mercado H (1996) Physical, chemical, and microbiological characteristics of dehydrated foods. In: Barbosa-Cánovas GV (ed) Dehydration of foods. Chapman & Hall, New York, pp 29–100
- Brujin J, Bórquez R (2014) Quality retention in strawberries dried by emerging dehydration methods. *Food Res Int* 63:42–48
- Cano-Chauca M, Ramos AM, Stringheta PC, Marques JA, Silva PI (2004) Curvas de secagem e avaliação da atividade de água da banana passa. *Boletim do Centro de Pesquisa de Processamento de Alimentos* 22:121–132
- Corzo O, Bracho N, Vásquez A, Pereira A (2010) Determination of suitable thin layer model for air drying of coroba slices (*Attalea Maripa*) at different air temperatures and velocities. *J Food Process Preserv* 34:587–598
- Farahnaky A, Ansari S, Majzoobi M (2009) Effect of glycerol on the moisture sorption isotherms of figs. *J Food Eng* 93:468–473
- Fernandes FAN, Rodrigues S, Gaspareto OCP, Oliveira EL (2006a) Optimization of osmotic dehydration of bananas followed by air-drying. *J Food Eng* 77:188–193
- Fernandes FAN, Rodrigues S, Gaspareto OCP, Oliveira EL (2006b) Optimization of osmotic dehydration of papaya followed by air-drying. *Food Res Int* 39:492–498
- Garcia CC, Caetano LC, de Souza Silva K, Mauro MA (2014) Influence of edible coating on the drying and quality of papaya (*Carica papaya*). *Food Bioprocess Technol* 7:2828–2839
- Hemis M, Raghavan GSV (2014) Effect of convective air attributes with microwave drying of soybean: model prediction and experimental validation. *Dry Technol* 32:543–549
- Hui L, Hetong L, Fang Y, Yife L, Yihui C (2011) Hot-air drying characteristics and kinetics model of litchi pulp. In: New technology of agricultural engineering (ICAE), 2011 International conference on. IEEE, pp 984–988
- Kaur K, Kumar S, Alam S (2014) Air drying kinetics and quality characteristics of oyster mushroom (*Pleurotus ostreatus*) influenced by osmotic dehydration. *Agric Eng Int CIGR J* 16:214–222
- Kaymak-Ertekin F, Gedik A (2004) Sorption isotherms and isosteric heat of sorption for grapes, apricots, apples and potatoes. *LWT-Food Sci Technol* 37:429–438
- Khan MR (2012) Osmotic dehydration technique for fruits preservation—A review. *Pak J Food Sci* 22:71–85
- Kowalski SJ, Mierzwa D (2013) Influence of osmotic pretreatment on kinetics of convective drying and quality of apples. *Dry Technol* 31:1849–1855
- Kowalski SJ, Szadzińska J (2014) Convective-intermittent drying of cherries preceded by ultrasonic assisted osmotic dehydration. *Chem Eng Process Process Intensif* 82:65–70

- Lenart A, Cerkowniak M (1996) Kinetics of convection drying of osmodehydrated apples. *Polish J Food Nutr Sci* 5:73–82
- Lopes de Menezes M, Ströher AP, Pereira NC, Barros TD (2013) Análise da cinética e ajustes de modelos matemáticos aos dados de secagem do bagaço do maracujá-amarelo. *Engevista* 15:176–186
- Nieto A, Castro MA, Alzamora SM (2001) Kinetics of moisture transfer during air drying of blanched and/or osmotically dehydrated mango. *J Food Eng* 50:175–185
- Puente-Díaz L, Echegaray-Pacheco E, Castro-Montero E, Di Scala K (2013) Aplicación de modelos matemáticos al proceso de secado asistido por infrarrojos de descartes de limón (*Citrus limon L.*) *Burm. F. Cv. Genova*). *Dyna* 80:91–97
- Qian Z, Zhenjiang G, Xuhai Y, Hongwei X, Zheng L, Junwen B, Fanbi M (2011) Model of air impingement drying on line pepper. In: 2011 International conference on new technology of agricultural engineering (ICAE), IEEE, 2011, pp 797–801
- Ruiz-López II, Huerta-Mora IR, Vivar-Vera MA, Martínez-Sánchez CE, Herman-Lara E (2010) Effect of osmotic dehydration on air-drying characteristics of chayote. *Dry Technol* 28:1201–1212
- Sacilik K, Elicin AK (2006) The thin layer drying characteristics of organic apple slices. *J Food Eng* 73:281–289
- Simal S, Deyá E, Frau M, Rosselló C (1997) Simple modelling of air drying curves of fresh and osmotically pre-dehydrated apple cubes. *J Food Eng* 33:139–150
- Singh B, Gupta AK (2007) Mass transfer kinetics and determination of effective diffusivity during convective dehydration of pre-osmosed carrot cubes. *J Food Eng* 79:459–470
- Unal HG, Sacilik K (2011) Drying characteristics of hawthorn fruits in a convective hot-air dryer. *J Food Process Preserv* 35:272–279
- Vega-Gálvez A, Puente-Díaz L, Lemus-Mondaca R, Miranda M, Torres MJ (2014) Mathematical modeling of thin-layer drying kinetics of cape gooseberry (*Physalis peruviana L.*). *J Food Process Preserv* 38:728–736
- Velić D, Planinić M, Tomas S, Bilić M (2004) Influence of airflow velocity on kinetics of convection apple drying. *J Food Eng* 64:97–102
- Velickova E, Winkelhausen E, Kuzmanova S (2014) Physical and sensory properties of ready to eat apple chips produced by osmo-convective drying. *J Food Sci Technol* 51:3691–3701
- Yan D, Jianwei J (2012) The characteristics and mathematical model of hot air drying Schisandra. In: 2012 International conference on measurement, information and control (MIC), IEEE, 2012, pp 1006–1010
- Yu H-M, Zuo C-C, Xie Q-J (2015) Drying characteristics and model of chinese hawthorn using microwave coupled with hot air. *Math Probl Eng*. doi:[10.1155/2015/480752](https://doi.org/10.1155/2015/480752)
- Zielinska M, Zapotoczny P, Alves-Filho O, Eikevik TM, Blaszcak W (2013) A multi-stage combined heat pump and microwave vacuum drying of green peas. *J Food Eng* 115:347–356