Study of the drying kinetics for apples in a convective drier

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Abstract

In the present work a convective drier was used to dehydrate apple slices up to a moisture content of less than 2 % (wet basis), so as to obtain a crunchy apple snack. Two commercial varieties were tested, namely Golden and Smith. The drier was operated at different temperatures, 30, 40 50 and 60 ºC, and the moisture content of the product was calculated based on the mass, which was registered by means of a data logger, throughout the whole trial. The kinetic data was then treated and fitted to different thin layer models frequently cited in literature, which were: Page, Henderson and Pabis, Logarithmic and Vega-Lemus. Others were also tested, but convergence was not achieved. For the fitting software SigmaPlot V8.0 (SPSS, Inc.) was used, and to evaluate the quality of the estimations the correlation coefficient (R) and the standard error of the estimate (SEE) were determined

From the models tested it was possible to see that the Vega-Lemus was the worst to describe the drying kinetic in the present case, on the other hand, the best model was the Page. Also the Fick's equation for diffusion was used to estimate the diffusivities at different temperatures, and from those to estimate the activation energy for moisture diffusion, which was found to be 35 kJ/mol for the drying of apples from Golden variety and 33 kJ/mol for the Smith variety.

Keywords: *apple; drying; kinetics; thin layer model.*

1. Introduction

Drying is a very important unit operation and is one of the most widely used primary methods for food preservation. It allows extending the shelf life of foods by removal of a great majority of water, and in this way the deterioration phenomena due to micro-organisms, enzymes and ferments is minimized. Besides preservation, other advantages are achieved with drying, such as lighter weight for transportation and less need of space for storage, or even avoiding expensive refrigeration systems (Guiné & Barroca, 2011).

In engineering terms, drying is a complex process which involves simultaneous transient heat and mass transfer phenomena, occurring both inside and at the border of the food. Many mathematical thin-layer models have been proposed to describe the drying process of agricultural materials, and in particular the semi-theoretical models are very frequently used (Doymaz, 2007; Guiné et al., n.a.).

The design of a drier is frequently carried out empirically and based on the extrapolation of knowledge existing for other cases. However, for reliable process modelling is very important the knowledge of the physical-chemical behavior of the food, as well as the drying kinetics, which accounts for the mechanisms of water removal (Guiné et al., 2007).

Simulation models are essential for the design of new drying systems as well as for the improvement of those already existing, besides allowing a better control of the drying operations. The drying kinetics may be described in terms of the transport properties of both, the material and the drying air (Guiné *et al.*, 2009). Thin layer models are equations that describe the drying phenomena in a combined way, regardless of the controlling mechanism, which are commonly used to fit the drying data. They express the variations in moisture along drying in terms of parameters such as the drying constant, k (1/s), or the lag factor, k_0 (dimensionless), that account for combined effects of various transport phenomena during drying (Tripathy & Kumar, 2009). Many different thin layer equations can be found in literature, varying widely in nature, and they have been used by many investigators to successfully explain the drying of several agricultural products (Togrul & Pehlivan, 2003; Nourhène *et al.*, 2008).

2. Materials and methods

2.1. Drying procedure

The apples were purchased at a local market, washed and peeled, and finally cut into semi-circles of approximately 0.5 cm thickness before drying. A convective hot air drying was carried out at 30 ℃, 40 ℃, 50 ℃ and 60 ℃, for e ach variety of apple tested, namely Granny Smith and Golden Delicious. While for the drying of the Golden Delicious apples the drying times were 10, 10, 16 and 37 hours, respectively for the temperatures of 30, 40 50 and 60 ºC, for the other apples, Granny Smith, the drying times were 10, 14, 19 and 38 hours, respectively for the same temperatures.

2.2 Moisture analysis

All analyses performed to the apples along drying were done with a Halogen Moisture Analyser HG53 from Mettler Toledo. The operational parameters used were 120 ºC and test speed 3.

2.3 Use of empirical models do describe the drying kinetics

The data obtained experimentally for the different temperatures studied was plotted in the form of the dimensionless variable moisture ratio $MR = (W-W_e)/(W_0-W_e)$ versus time, where W, W_e and W_0 are, respectively, the moisture content at time t, the equilibrium moisture content and the initial moisture content, all expressed in dry basis (g water/ g dry solids) (Mota *et al.*, 2010). W_e was considered to be 0.01 g water/g dry solids, and corresponds to the drying for a very long period when the equilibrium with the surrounding atmosphere was achieved. The experimental sets of (MR, t) were fitted to different empirical models from literature, cited by Baini & Langrish (2007) and Guiné et al. (2009) which are presented in Table 1. For that the software Sigma Plot, v 8.0 was used, and to evaluate the quality of each estimation, some statistical information was also determined, namely the correlation coefficient (R) and the standard error of the estimate (SEE).

TABLE 1: Empirical models to represent the drying kinetics.

Model name	**Equation**
Page	$MR = \exp(-k t^n)$
Henderson & Pabis	$MR = a \exp(-k t)$
Logarithmic	$MR = a \exp(-k t) + c$
Vega-Lemus	$MR = (a + k t)^2$

2.5. Estimation of the diffusion coefficients

Fick's second law equation for non steady-state diffusion, assuming that the samples used can be approximated to slabs, the diffusion is expressed by (Crank, 1975):

$$\frac{\partial W}{\partial t} = D_e \left(\frac{\partial^2 W}{\partial r^2} \right) \qquad (1)$$

where D_e is effective moisture diffusivity, t is the time, expressed in seconds and r is the spatial coordinate, varying from o to L.

Assuming uniform initial moisture content and a constant effective diffusivity throughout the sample, the analytical solution of Eq. (3) is given by:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-D_e \frac{(2n+1)^2 \pi^2}{4L^2} t \right] \qquad (2)$$

Considering only the first term of the series, the solution of the Fick's Equation becomes:

$$MR = \frac{8}{\pi^2} \exp\left[-D_e \frac{\pi^2}{4L^2} t \right] \qquad (3)$$

and a plot of ln(MR) versus time for each temperature will give a straight line whose slope can allow to estimate the value of diffusion coefficient for each temperature.

The dependence of the effective diffusivity from temperature is assumed to be an Arrhenius function (Vega et al., 2007), of the type:

$$D_e = D_e^0 \exp\left(-\frac{E}{R_g T} \right) \qquad (4)$$

where D_e^0 is the diffusivity for an infinite temperature, E is the activation energy for moisture diffusion, R_g is the gas constant (R_g = 8.31451 J mol^{-1} K^{-1}) and T is the drying temperature (expressed in ℃). A plot of ln(D_e) as a function of (1/(T + 273.15)) will produce a straight line with slope equal to ($-E/R$) and intercept equal to Ln(D_e^0), from which the parameters E and D_e^0 can be estimated.

3. Results and discussion

The drying kinetics data obtained for the four temperatures studied, in the form of humidity ratio versus time was fitted to four different kinetic models commonly cited in literature, as shown in Table 1. The results of the statistical evaluation made to the fits for the different temperatures and different models are presented in Table 2, which shows the values of the correlation coefficients (R) and standard errors of the estimate (SEE).

The criterion followed for selecting the model that best represents the process of drying apples was the values of both statistical parameters calculated: the correlation coefficient (R) and standard errors of the estimate (SEE). From the results it was concluded that the best model for the case at study was the Page model. Of all models, the Page model was the one that presented the correlation coefficients (R) closer to 1 together with the lowest values of the standard errors of the estimates (SEE). For Page model R varied between 0.9989 and 0.9997 for the Golden variety and between 0.9989 and 0.9998 for the variety Smith. As to the values of SEE they ranged between 0.0058 and 0.0090 for the Golden Variety and between 0.0057 and 0.0085 for the Smith variety. Comparing all models tested it was possible to see that the Vega-Lemus was the worst to describe the drying kinetic in the present case, with the lower values for R and higher SEE. In this case R varied between 0.8745 and 0.9132 for the Golden variety and between 0.8584 and 0.9276 for Smith. The values of SEE ranged between 0.0936 and 0.1152 for the Golden apples and between 0.0857 and 0.1085 for the Smith.

TABLE 2: Statistical evaluation of the fits with the different models.

Variety Golden					
Model	**Statistics**	**30 ºC**	**40 ºC**	**50 ºC**	**60 ºC**
Page	R	0.9989	0.9992	0.9995	0.9997
	SEE	0.0090	0.0090	0.0075	0.0058
Henderson & Pabis	R	0.9939	0.9900	0.9927	0.9938
	SEE	0.0216	0.0318	0.0293	0.0287
Logarithmic	R	0.9946	0.9920	0.9941	0.9954
	SEE	0.0205	0.0289	0.0270	0.0255
Vega-Lemus	R	0.8745	0.9099	0.9132	0.8941
	SEE	0.0954	0.0936	0.0988	0.1152
Variety Smith					
Model	**Statistics**	**30 ºC**	**40 ºC**	**50 ºC**	**60 ºC**
Page	R	0.9989	0.9994	0.9994	0.9998
	SEE	0.0085	0.0081	0.0084	0.0057
Henderson & Pabis	R	0.9901	0.9931	0.9992	0.9968
	SEE	0.0256	0.0269	0.0096	0.0207
Logarithmic	R	0.9907	0.9955	0.9993	0.9973
	SEE	0.0251	0.0221	0.0095	0.0196
Vega-Lemus	R	0.8584	0.9276	0.9130	0.9095
	SEE	0.0938	0.0857	0.1007	0.1085

R = correlation coefficient, SEE = standard error of the estimate.

Table 3 shows the values estimated for the parameters *k* and *n* in the Page model, for both varieties of apples. In general the parameter *k* represents the effect of external conditions of drying, while the *n* reflects the extent of internal resistance to drying of the product to certain external conditions (Misra & Brooker, 1980). The values of the coefficients *k* and *n* are variable, depending on the type of product and drying air temperature.

TABLE 3: Parameters estimated for the Page model.

Drying temperature	**Variety Golden**		**Variety Smith**	
	k	**n**	**k**	**n**
30ºC	0.0006	0.7872	0.0014	0.7184
40ºC	0.0017	0.7305	0.0009	0.7745
50ºC	0.0016	0.7552	0.0002	0.9600
60ºC	0.0023	0.7486	0.0011	0.8211

Fig. 1 (a) and (b) illustrate the variations of wet basis moisture content for the apples from varieties Golden and Smith, respectively, during air convection drying at different temperatures. The batch drying curves obtained at temperatures of 30 ℃, 40 ℃, 50 ℃ and 60 ℃ showed a quite similar kinetic behavior for b oth varieties not showing a constant rate period of drying, corresponding to the initial heating phase. Therefore, in all cases the drying rate starts immediately to decrease, and very rapidly too.

Samples of the variety Golden reached a final moisture content of 2.61, 2.60, 1.75 and 1.51 % (wet basis), for temperatures of 30, 40, 50 and 60C, respectively, while for the Smith variety, the final moisture contents were 1.81, 1.68, 1.39 and 1.26 % respectively for the same temperatures. Furthermore, while for variety Golden stabilization was achieved at around 30, 15, 12 and 9 hours, respectively for temperatures of 30, 40, 50 and 60 ºC, for the apples from variety smith the times were inferior: 23, 17, 15 and 8 hours. As expected, there is an acceleration of the drying process, due to the increase in temperature of the drying air from 30 ℃ to 60 ℃, substantially reducing the processing time.

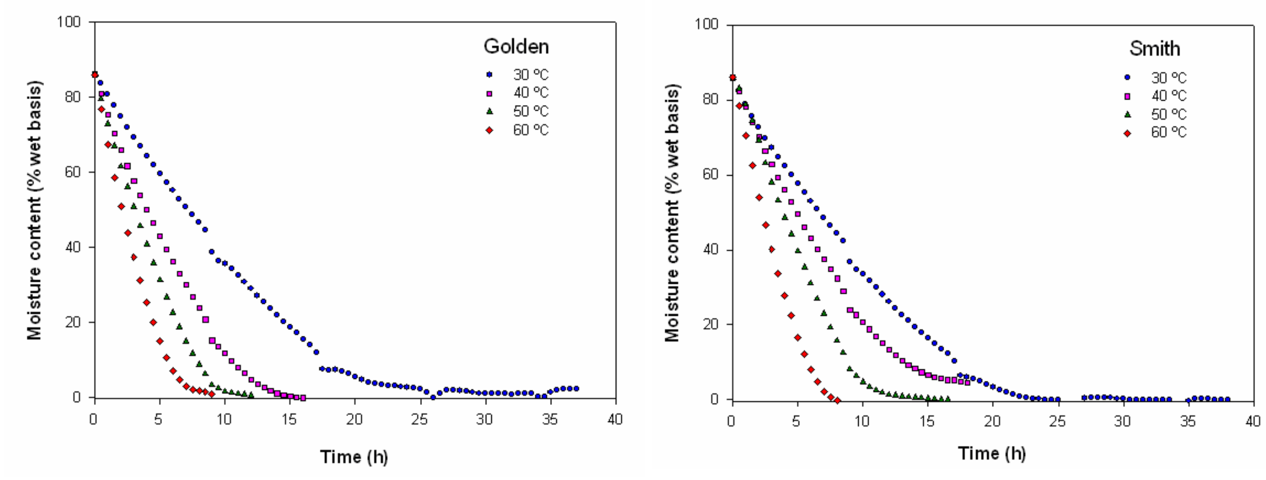

FIGURE 1: Variation along drying of the moisture content for:
(a) Golden delicious apples (b) Granny Smith apples.

Fig. 2 (a) and (b) show the variations along drying of the moisture ratio (RM) for each of the temperatures for the two varieties of apples, Golden and Smith, respectively. It is possible to observe from the graphs that the fits obtained with the Page model describe with reasonable accuracy the drying behavior of both varieties of apples studied, since the curves stand very close to the experimental points.

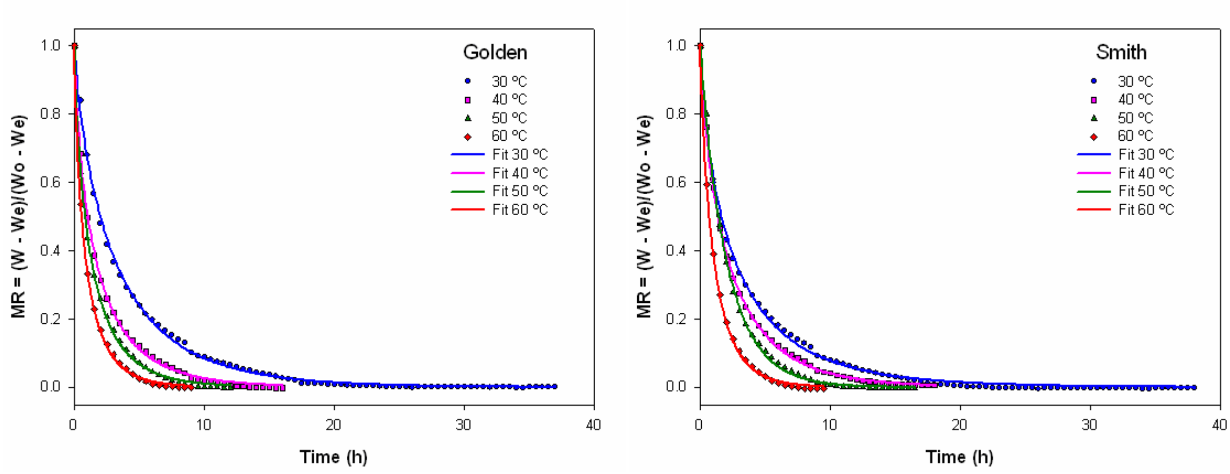

FIGURE 2: Fitting of the experimental points to the Page model for:
(a) Golden delicious apples (b) Granny Smith apples.

Table 4 shows the values of the diffusivities estimated according to Fick's law, Equation (4), for both varieties, and the results show that in both cases the diffusivities are very similar among varieties and that there is an important increase in diffusivity as temperature raises. Furthermore, in the same Table are also presented the values estimated in both cases for the parameters in the Arrhenius relation between diffusivity and temperature, Equation (5). It was estimated from the data obtained in the present study that the activation energy for diffusion is 35 kJ/mol for apples of the variety Golden and 33 kJ/mol for the Smith apples.

4. Conclusions

From the results obtained it was observed that temperature exerts a great influence on the rate of convective drying of apples from varieties Golden and Smith. It was observed that the higher the drying temperature, the greater the drying rate and thus an important reduction in drying time was achieved.

To model the drying kinetics four different thin-layer drying models were tested. Based on the results from this work, it was concluded that the Page model adequately describes the drying process of the two varieties of apples, for all temperatures used. Apart from modeling the drying kinetics in terms of thin layer models, the Fick's equation for diffusion was used to estimate the diffusivities at different temperatures, and those were then used to estimate the activation energy for moisture diffusion, which was found to be 35 kJ/mol for the drying of apples from Golden variety and 33 kJ/mol for the Smith variety.

TABLE 4: Diffusivities estimated according to Fick's law and Arrhenius relationship.

Drying temperature	**Diffusivity (m^2/s)**	
	Golden	**Smith**
30 ºC	4.22×10^{-10}	4.65×10^{-10}
40 ºC	7.89×10^{-10}	4.98×10^{-10}
50 ºC	11.67×10^{-10}	10.10×10^{-10}
60 ºC	14.92×10^{-10}	13.57×10^{-10}
Parameters	**Estimations**	
	Golden	**Smith**
D_e^0 (m^2/s)	5.46×10^{-4}	1.84×10^{-4}
E (kJ/mol)	35.26	32.78

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