Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar

Spanish Journal of Agricultural Research 2009 7(4), 869-875
ISSN: 1695-971-X

Dehydration kinetics of carrots (*Daucus carota* L.) in osmotic and air convective drying processes

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Abstract

This paper presents a kinetic study of osmotic dehydration and air drying with and without osmotic pre-treatment of carrot. Carrot cylinders of different diameters (4.5, 7 and 9 mm) were employed and, osmotic solutions of sodium chloride of different concentrations (17, 22 and 26% w/w) at various process temperatures (25, 35 and 45°C) and contact times (up to 180 min). The water loss (kg kg^{-1}) and the solid gain (kg kg^{-1}) in the samples increase with temperature and solution concentration increase. These parameters also depend on size (specific area) of the samples. The drying rate (kg water kg^{-1} dry solid h^{-1}) increases with temperature and decreases with the sample diameter. Experimental drying kinetics were fitted satisfactorily to a first order (simple model) kinetics (where the parameter k_s ranges from 0.1748 up to 0.6691 h^{-1}) and to the Page model [where the parameters k_p (h^{-n}) and n (–) range from 0.1592 and 1.0683 up to 0.6451 and 1.300, respectively] in order to determine the kinetic constants during drying. Osmotic dehydration combined with the air drying has proven to be an interesting method to reduce water in the samples without extreme thermal processes, nevertheless, the drying rate of the samples previously treated during 1 hour with osmotic dehydration decreased about 13%.

Additional keywords: air temperature, drying kinetic parameters, sample size, solid gain, water loss.

Resumen

Cinéticas de la deshidratación de zanahorias (*Daucus carota* L.) en procesos osmóticos y de secado convectivo con aire

En este trabajo se ha realizado un estudio cinético de la deshidratación osmótica y del secado con aire sin y con pretratamiento osmótico de la zanahoria. Se utilizaron cilindros de zanahoria de diferentes diámetros (4,5; 7 y 9 mm) y disoluciones osmóticas de cloruro sódico de distintas concentraciones (17, 22 y 26% en peso) a varias temperaturas de proceso (25, 35 y 45°C) y tiempos de contacto (hasta 180 min). La pérdida de agua (kg kg^{-1}) y la ganancia de sólidos (kg kg^{-1}) en las muestras aumentaron con la temperatura y la concentración de la disolución. Estos parámetros también dependieron del tamaño (área específica) de las muestras. La velocidad de secado (kg kg^{-1} de sólido seco h^{-1}) aumentó con la temperatura y disminuyó con el diámetro de muestra. Se ajustaron los datos experimentales satisfactoriamente a una cinética de primer orden, modelo simple (donde el parámetro k_s varía desde 0,1748 hasta 0,6691 h^{-1}) y al modelo de Page [donde el parámetro k_p (h^{-n}) y n (–) varían desde 0,1592 y 1,0683 hasta 0,6451 y 1,300, respectivamente] para determinar las constantes cinéticas durante el secado. La deshidratación osmótica combinada con el secado con aire resulta ser un método interesante para reducir el agua de las muestras sin procesos térmicos extremos, sin embargo, la velocidad de secado de las muestras previamente tratadas con 1 hora de deshidratación osmótica disminuye en torno a un 13%.

Palabras clave adicionales: ganancia de sólidos, parámetros cinéticos de secado, pérdida de agua, tamaño de muestra, temperatura del aire.

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Received: 12-11-08; Accepted: 26-08-09.

Abbreviations used: d (diameter, mm), *ks* (kinetic parameter of simple model, h^{-1}), *kp* (kinetic parameter of Page model, h^{-n}), m (total mass, kg), n (kinetic parameter of Page model, -), NC (natural convection), *NMC* (normalized moisture content, kg kg^{-1}), *NSC* (normalized solid content, kg kg^{-1}), OD (osmotic dehydration), r^2 (coefficient of determination, –), S (dry solid mass, kg), *SG* (solid gain, kg kg^{-1}), *WL* (water loss, kg kg^{-1}), *X* (moisture content, kg water kg^{-1} dry solid), *X** (equilibrium moisture content, kg water kg^{-1} dry solid).

Introduction

The vast majority of food products, particularly those of plant origin, are specific to a particular time of year. Fortunately, through the appropriate application of current technology, the availability of perishable food products can be increased, contributing in a useful way to human welfare.

Water is the principal component of food products and its presence contributes significantly to their aging and deteriorating. Therefore, the water content removal from a food product reduces the possibility of its biological alteration and the velocity of the degradation mechanisms.

The main purpose of conservation processes based on reducing the water content is to prolong the shelf life of food products. In addition, the water removal can also reduce their weight significantly, which leads to significant economic savings both with regard to transport and maintenance (Jayaraman and Das Gupta, 1992).

This study has used osmotic dehydration and convective drying as conservation methods of carrot. The carrot is a seasonal product (autumn and winter), and it is a major source of sugars, vitamins (B1, B2, B6 and B12) and β-carotene, precursor of vitamin A (Bureau and Bushway, 1986; Bao and Chang, 1994); that is why it is so important in food, especially for children. There are numerous works on the drying of this product (Mulet *et al.*, 1987, 1989; Prabhanjan *et al.*, 1995; Rastogi and Raghavarao, 1997; Qi *et al.*, 1998; Kumar *et al.*, 2001; Doymaz, 2004; Jezek *et al.*, 2006; Singh *et al.*, 2006; Górnicki and Kaleta, 2007), since the carrot is, after the potato, the world's most widely grown tuber crop.

The osmotic dehydration (OD) enables the water removal from the food by immersing the product in a hypertonic solution (of certain solutes). A water transfer takes place from the food product to the solution and a solid transfer from the solution to the food product (Matusek and Méresz, 2002).

The hot-air drying process by means of natural convection (NC) is a simultaneous process of heat and mass transfer, accompanied by a phase change. There are four transport processes: heat transfer from the air to the solid surface, heat transfer from the air-solid interface to the solid interior, mass transfer through the solid and vapour transfer from the air-solid interface into the bulk of the air flow.

However, the sample quality decreases with drying temperature increases (Suvarnakuta *et al.*, 2005). The physical, texture and nutritional characteristics of food products are modified due to heat treatments (Krokida *et al.*, 2000a,b). In this regard, the osmotic treatments, previous to air-drying process (Lewicki *et al.*, 2002; Rastogi *et al.*, 2004; Revaskar *et al.*, 2007) improve the nutritional, sensory and functional characteristics of dehydrated food products. They may even improve the texture and the stability of pigments during the dehydration and storage of dehydrated products.

In this paper the carrot dehydration kinetics during the osmotic dehydration and the drying by natural convection with and without osmotic pre-treatment is studied. The tests are carried out systematically and cover a wide range of solution concentration, temperature and size of samples, from which the kinetic parameters were obtained for the operating conditions studied.

Material and methods

Samples of Nantes carrots with cylindrical geometry (4.5, 7 and 9 mm diameter, and 16 mm length) were selected. Five samples with defined dimensions were used in each experiment. The weight of the samples is controlled over time by means of a Sartorius BP 210 S (± 0.0001 g) analytical balance.

Several tests are carried out with samples subject to osmotic dehydration, using different concentration (17, 22 and 26% w/w) of sodium chloride with 99.9% purity at different experiment durations (15, 30, 60, 120 and 180 min) at 25°C. The samples are introduced into hermetically closed vessels with a specific volume of concentrated salt solution (with volumetric ratio solution/sample > 10, to avoid dilution phenomena during the osmotic process). The vessels are kept at a given temperature inside a thermostatic bath and after the processing time samples are removed out of the vessels and dried with paper filter in order to eliminate fluid excess. The samples are weighed and put into an oven (K Tarma) at 95°C until achieving a constant weight, in order to know the solid content of the samples subjected to osmotic dehydration. The temperature effect (25, 35 and 45°C) is studied on osmotically dehydrated samples employing the most concentrated NaCl solutions (26% w/w).

Different parameters characteristic of the osmotic dehydration process (Moreira and Sereno, 2003; Singh *et al.*, 2007), are analysed.

The water loss (*WL*) and the normalized moisture content (*NMC*) quantify the loss of moisture within the osmotic dehydration process and can be calculated as:

$$WL = \frac{(m_0 - S_0) - (m - S)}{(m_0 - S_0)} \quad [1]$$

$$NMC = \frac{X}{X_0} \quad [2]$$

The solid gained (*SG*) represents the amount of salt that the food product tissue gains from the osmotic solution in relation to its initial weight and is expressed by:

$$SG = \frac{(S - S_0)}{m_0} \quad [3]$$

The normalized solid content (*NSC*) proves the relationship between the solid content at a specific moment in time and the initial content:

$$NSC = \frac{S}{S_0} \quad [4]$$

In order to carry out the hot-air drying by natural convection, samples are introduced into an oven (P Selecta, ± 1°C) at 40 or 55°C. The weight of the samples is controlled using the analytical balance Sartorius over time. At the end of the experiment the solid content of the samples is determined after being introduced in an oven at 95°C for the time necessary to achieve a constant weight.

The kinetics relating to different drying temperatures and to samples of various diameters are assessed in this study. A fit of the moisture content curves versus time to a first order kinetics is also carried out. This model is known as a simple model (exponential) whose mathematical expression is (Krokida *et al.*, 2003; Senadeera *et al.*, 2003; Simal *et al.*, 2005; Vega-Gálvez *et al.*, 2008):

$$\frac{X - X^*}{X_0 - X^*} = e^{-k_s t} \quad [5]$$

The term on the left side of the Eq. [5] corresponds to the normalized moisture.

The empirical Page model has also been used to fit the experimental data, and good results have been obtained in several works (Prabhanjan *et al.*, 1995; Senadeera *et al.*, 2003; Doymaz, 2004; Simal *et al.*, 2005):

$$\frac{X - X^*}{X_0 - X^*} = e^{-k_p t^n} \quad [6]$$

In the Eqs. [5] and [6] X^* can be usually negligible (whereas X is high or X^* value is very low like is habitually in the conditions with high temperature and low relative humidity employed during drying) in order to simplify the mathematical procedure. In this case, the left term of the Eqs. [5] and [6] corresponds to *NMC* (Eq. [4]).

Carrot samples were osmotically pre-treated for one hour, subsequently undergoing an air-flow drying process at 40°C in order to study the influence of the osmotic pre-treatment on the convective drying kinetics. For this assay, the highest sodium chloride concentration (26% w/w) was selected in order to accelerate the water removal but temperature was the lowest (40°C) in order to minimize the changes of colour in carrots.

Results

The evolution of *WL* with time for different sizes of carrots is shown in Figure 1. It is observed that, under the experimental conditions tested, the water removal kinetics is considerably fast, since after 1 hour at most, the samples practically reach constant water loss values. In particular, for the smaller samples the water loss is even faster, and that the stationary value is already reached during the first 30 min. On the other hand, when representing *NMC*, whose value is affected simultaneously by the rate of water removal and the acquisition of osmotic solute, versus the process time (Fig. 2) there are two different areas, regardless of the temperature of the test: first, until 1 hour treatment, the value of *NMC* decreases sharply, whereas from that time, the value of *NMC* remains fairly constant. As

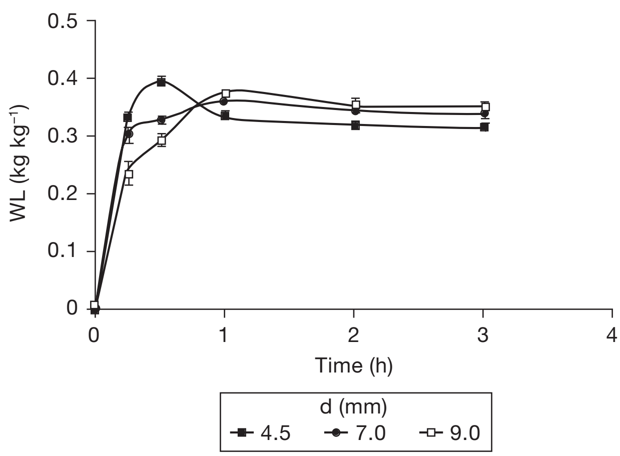

Figure 1. Water loss (*WL*) evolution with time for samples of different diameters (d). OD: 26% w/w NaCl concentration and 45°C.

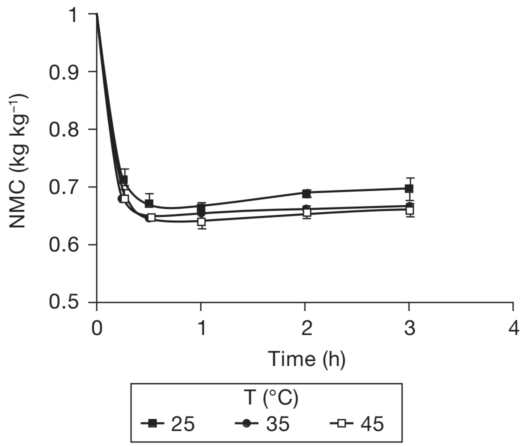

Figure 2. Normalized moisture content (*NMC*) evolution with time at different temperatures. OD: 26% w/w salt concentration and diameter of samples of 7 mm.

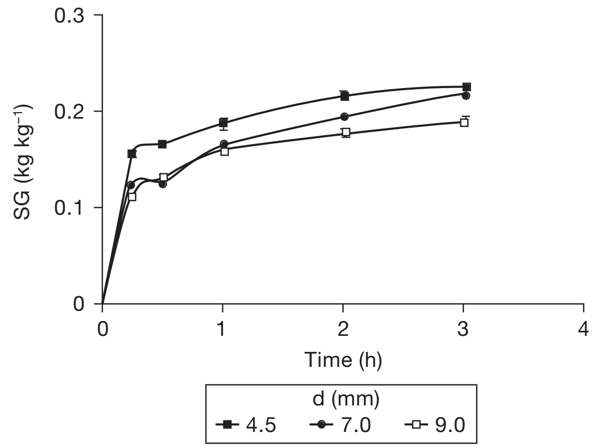

Figure 4. Solid gain (*SG*) evolution with time for different sample diameters (d). OD: 26% w/w salt concentration and 45°C.

expected, the decreasing rate in the value of *NMC* increases with temperature employed.

In Figure 3, the influence of the osmotic solution concentration on the *NMC* parameter is shown. The results indicate that the *NMC* at the end of the process decreases as the concentration is increased and, therefore, the transfer rate increases with this variable. This is due to the fact that, by increasing the concentration of salt in the osmotic solution, the driving force that governs the process of mass transfer is increased too. In all subsequent trials 26% w/w salt concentration is chosen.

Figures 4 and 5 show the evolution of solid gain (*SG*) and the *NSC* parameter with time, respectively, giving an idea of the effect that the temperature and the diameter of the samples have on the process. Unlike the analysis of water removal kinetics, in this case it is noticeable that although this process also occurs quickly in the early moments of the contact between the sample and the osmotic solution, for the solute acquisition kinetics a completely stationary value is not reached at the end of the experiment time. This fact highlights that the processes of osmotic solute diffusion into the carrots are not fully developed. A further analysis shows that the solid gain increases when raising the temperature and reducing the sample size. These results confirm that the acquisition of solutes is primarily carried out at the surface because the samples with a smaller diameter generate greater specific contact surface. Based on the convective hot-air drying tests, kinetic constants are calculated for different drying temperatures as well as for various diameters of samples using the models shown in Eqs. [5] and [6].

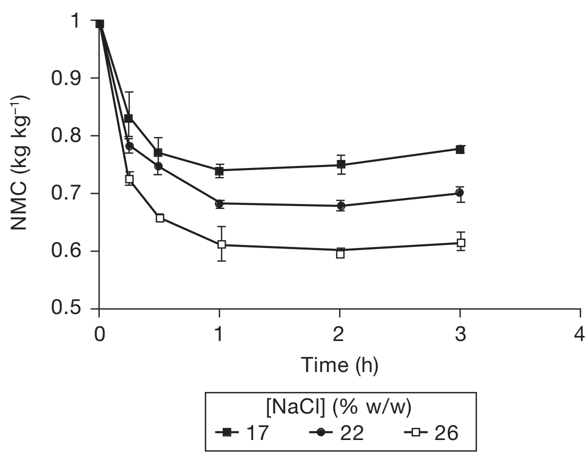

Figure 3. Normalized moisture content (*NMC*) evolution with time at different NaCl concentrations. OD: 25°C and diameter of samples 7 mm.

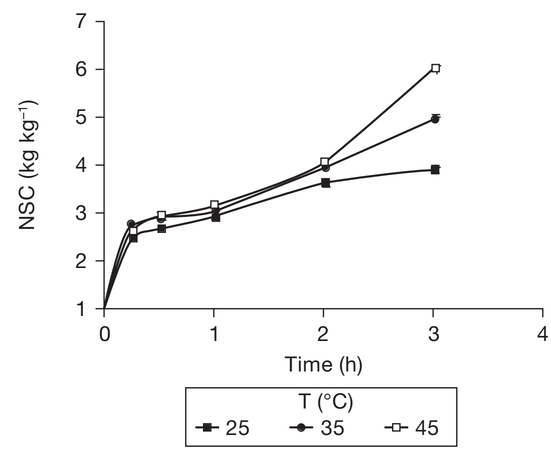

Figure 5. Normalized solid content (*NSC*) evolution with time at different temperatures. OD: 26% w/w salt concentration and diameter of samples of 7 mm.

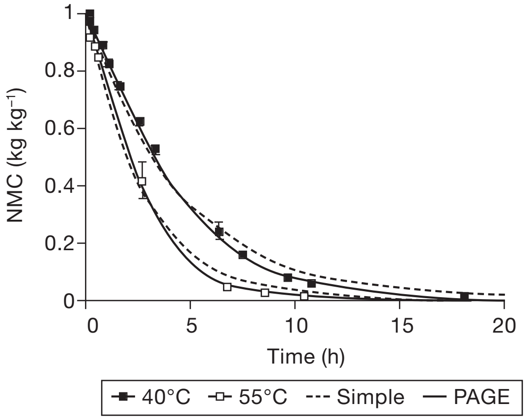

Figure 6. Influence of temperature on the convective drying of samples with diameter of 7 mm.

Table 1. Parameter of simple model (Eq. [5]), k_s (h^{-1}), for air drying by natural convection (NC) of carrots at different temperatures and osmotic dehydration (OD) treatment

Process conditions	Diameter (mm)		
	9	7	4.5
40°C NC			
k_s (h^{-1})	0.1748	0.2290	0.3447
r^2	0.998	0.996	0.992
55°C NC			
k_s (h^{-1})	0.2852	0.3705	0.6691
r^2	0.992	0.996	0.995
1 h OD+ 40°C NC			
k_s (h^{-1})		0.1998	
r^2		0.992	

Figure 6 shows the variation in the *NMC* with time for various operating temperatures and corresponding fits to the models listed. Figure 7 shows how normalized moisture varies over time depending on the sample size. The results for the dehydration constant of the simple model (Eq. [5]) are presented in Table 1, where it can be noticed that the convective drying rate increases with temperature and decreases with the sample thickness. The results obtained for the constants of Page's model (Eq. [6]) are shown in Table 2, where the trend of the fitting parameters is similar to the one shown by the simple model.

The results for the combined process (convective hot-air drying with an osmotic pre-treatment) are shown in Figure 8, showing the behaviour of the samples that had been osmotically pre-treated compared with samples that have dried only by natural convection. In the first case moisture content decreases more slowly, due to the presence of the salt absorbed in the process of osmotic dehydration, which prevents the water removal. Thus, for 7 mm carrot samples, dried at 40°C with osmotic pre-treatment for 1 hour, the kinetic constants obtained with simple model and Page model are lower than those obtained without pre-treatment (Tables 1 and 2).

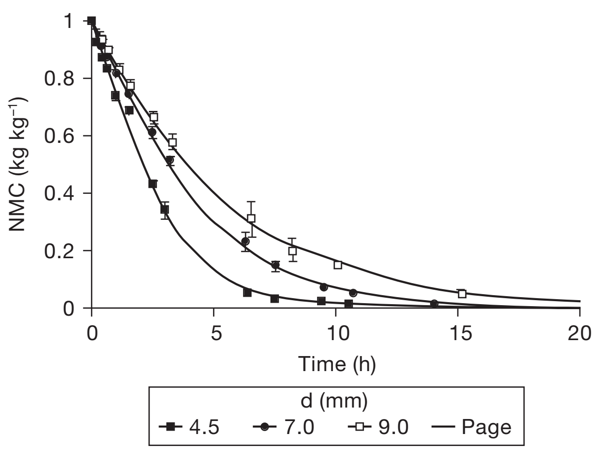

Figure 7. Influence of the diameter of samples on convective drying at 40°C.

Discussion

In spite of the existence of greater surface area, increasing the diameter of the samples causes a decrease in the specific area and therefore the duration of the

Table 2. Parameters of Page model (Eq. [6]), k_p (h^{-n}) and n (–), for air drying by natural convection (NC) of carrots at different temperatures and osmotic dehydration (OD) treatment

Process conditions	Diameter (mm)		
	9	7	4.5
40°C			
k_p (h^{-n})	0.1592	0.1815	0.2807
n	1.0683	1.1676	1.2285
r^2	0.999	0.999	0.997
55°C			
k_p (h^{-n})	0.1879	0.2968	0.6451
n	1.3000	1.2146	1.2481
r^2	0.999	0.999	0.999
1 h OD + 40°C NC			
k_p (h^{-n})		0.1512	
n		1.1567	
r^2		0.993	

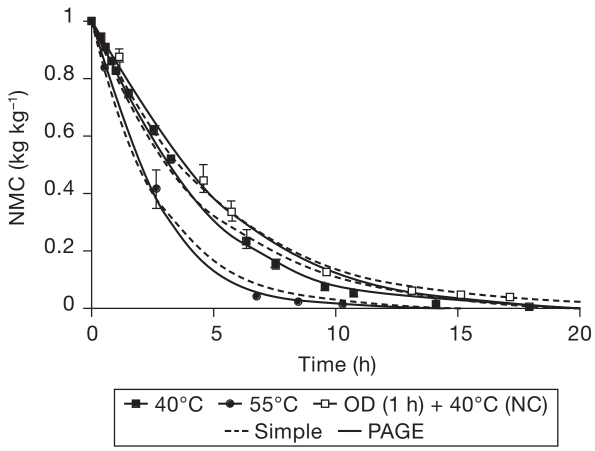

Figure 8. Normalized moisture content (*NMC*) evolution with time in convective drying (NC: 40 and 55°C, diameter of sample 7 mm) and in the combined process of osmotic dehydration (OD: 1 h, 26% w/w salt concentration, diameter of samples of 7 mm and 25°C) and convective drying (NC: 40°C and diameter of samples of 7 mm).

first phase of osmotic dehydration increases and the speed of water loss and solids gain decreases. This is due to the existence of greater resistance to transport by diffusion due to increased thickness that hinders the water exit and solid entry into the sample.

The degree of carrot dehydration increases when increasing the concentration of sodium chloride of the osmotic solution, and the dehydration temperature. It also increases during the first hour when increasing the time of the osmotic dehydration (Figs. 2 and 3).

The solid gain during the process of osmotic dehydration increases when reducing the sample thickness, but the water loss undergoes fluctuations throughout the process (Figs. 1 and 4).

The drying rate constants of the simple model and Page model increase with temperature. Thus, the convective drying rate increases with temperature and decreases if the sample thickness increases; Page's empirical model is better adapted to the experimental data than the simple model (Fig. 6). The kinetic parameters obtained follow the same trends as those presented in other works (Prabhanjan *et al.,* 1995; Doymaz, 2004).

In the combined process moisture content decreases more slowly, since the salt in the samples pre-treated hinders the water removal (Kumar *et al.*, 2001; Lewicki *et al.*, 2002). This fact is reflected in the values of the kinetic constants of the models used, which are lower for the experiments with samples treated by osmotic pre-treatment than in the case of untreated samples (Tables 1 and 2).

However, although the drying rate is lower in samples of osmotically treated carrots, this osmotic pre-treatment has advantageous effects over traditional methods compared with dehydration average levels, both in terms of energy as in terms of organoleptic and nutritional qualities of the product subject to experiment (Krokida *et al.*, 2000a,b; Suvarnakuta *et al.*, 2005).

Acknowledgements

The authors acknowledge the financial support to *Ministerio de Educación y Ciencia* of Spain and FEDER (CTQ 2007-62009/PPQ).

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