Dehydration kinetics of onion slices in osmotic and air convective drying process

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Abstract

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The effect of different pre-treatments (*i.e.* osmotic dehydration in 10, 15 and 20°Brix NaCl solution and drying air temperature of 50, 60 and 70°C) on drying behaviour of onion slices were investigated. The onion slices were dried in a laboratory model tray dryer. Drying of onion slices occurred in falling rate period. Five thin-layer drying models (Exponential, Page, Henderson and Pabis, Logarithmic and Power law) were fitted to the moisture ratio data. Among the drying models investigated, the Page model satisfactorily described the drying behaviour of onion slices. The effective moisture diffusivity of pre-treated samples was higher than that of non-treated samples.

Keywords: onion; drying; mathematical models; diffusivity; osmotic dehydration

Onion (*Allium cepa*), a very commonly used vegetable, ranks third in the world production of major vegetables (Mitra et al. 2012). In the manufacture of processed foods such as soups, sauces, salad dressings, sausage and meat products, packet food and many other convenience foods, dehydrated onion is normally used as flavour additive, being preferred to the fresh product, because it has better storage properties and is easy to use (Rapusas, Driscoll 1995; Kaymak-Ertekin, Gedik 2005). Onion is an important vegetable to serve as ingredients in dishes, as toppings on burgers, in seasonings, as chip coatings etc. (Sharma et al. 2005a).

Conventional air-drying is a simultaneous heat and mass transfer process, accompanied by phase change (Barbanti et al. 1994) being a high cost process. However, water removal using high temperatures and long drying times may cause serious decreases in nutritive and sensorial values, damaging mainly the flavour, colour and nutrients of dried products (Lenart 1996; Lin et al. 1998). Osmotic dehydration was used as pre-treatment to reduce air drying time and improve the product quality (Torreggiani 1993; Jayaraman, Gupta 1995; Karathanos et al. 1995; Sereno et al. 2001; Revaskar et al. 2007). Other advantages include limited heat damage, improved textural quality, vitamin retention, flavour enhancement and colour stabilization (Ade-Omowaye et al. 2003).

Osmotic dehydration is the most reported pretreatment used prior to air-drying (Lombard et al. 2008; Mundada et al. 2010). It removes water from the fruit or vegetable up to a certain level, which is still high for food preservation so that this process must be followed by another process in order to lower even more the fruit water content. It is a useful technique that involves the immersion of the fruit in a hypertonic aqueous solution leading to the loss of water through the cell wall membranes of the fruit and subsequent flow along the inter-cellular space before diffusing into the solution (Sereno et al. 2001). As a partial dehydration process, osmosis may be regarded as a simultaneous water and solute diffusion operation, wherein the sample incurs a gain of solids and a simultaneous loss of moisture (McMinn, Magee 1999b). The shelf life quality of the final product is better than without such treatment due to the increase in sugar/acid ratio, the improvement in texture and the stability of the colour pigment during storage (Lombard et al. 2008).

Osmotic dehydration combined with drying technologies provides an opportunity to produce novel shelf stable types of high quality product. The drying kinetics of food is a complex phenomenon and requires simple representations to predict the drying behaviour, and to optimize the drying parameters. Recently, studies were done on drying kinetics of fruits and vegetables (Togrul, Pehlivan 2002; Doymaz 2004; Jain, Pathare 2004; Akpinar, Bicer 2005; Sharma et al. 2005a; Goyal et al. 2006; Mundada et al. 2010). However, very limited studies were found in the literature which relate to the influence of pre-treatments, i.e. osmotic dehydration, on drying kinetics of onion. The objective of this study was (i) to investigate the influence of pre-treatments and drying air temperature on the drying behaviour of onion, (ii) to evaluate a suitable thin-layer drying model for describing the drying process, and (iii) to calculate the effective moisture diffusivity.

MATERIALS AND METHODS

Raw material. The fresh white onion bulbs (cv. V-12) were used in the present study. The white onion bulbs were stored in storage chamber maintained at a temperature of 4 ± 1°C and 70% air relative humidity until experiments were completed. Onions were taken from the storage and were allowed to equilibrate with ambient conditions for about 2 h followed by hand peeling. The peeled onions were cut into circular slices of thickness equal to 4 ± 0.1 mm using a manual stainless steel cutter. A sample size of about 200 g was used in each drying experiment. Initial moisture content of each sample was determined using the oven drying method which ranged between 4.56 and 5.45 g H_2O/g dry matter (DM).

Osmotic dehydration. The onion slices were partially dehydrated using osmotic drying technique. The slices were placed in different containers holding 10, 15 and 20°Brix of NaCl solution at ambient temperature (30°C) for 1 h; and stirring of the solution was done at regular intervals of 15 minutes. Solution to sample ratio was kept as 2.5:1 in each experiment. After a period of 1 h, slices were removed quickly and blotted gently using a tissue paper to remove the surface moisture.

Hot air drying. Samples non-treated and pre-treated in osmotic solution (10, 15 and 20°Brix NaCl solution) were dried in a laboratory tray dryer. The dryer consisted of a drying chamber, electric heater, fan and a temperature controller. Experiments were conducted at 50, 60 and 70°C air temperature and at a constant airflow velocity of 1.5 m/s. Slices of raw onion samples were uniformly spread in each trays and kept in dryer. Moisture loss was recorded in 5 min interval for an hour, then the weighing interval was increased to 10 min for next one hour; further readings were taken at 15 min interval by a digital balance of 0.01 g accuracy. The drying continued till the final moisture content of about 0.07 g water per g dry matter was reached in the dried product. Experiments were replicated three times. In total, 12 treatments combination as described in Table 1 were conducted.

Mathematical modelling. Mathematical modelling is essential to predict and simulate the drying behaviour. It is also an important tool in dryer's design, contributing to a better understanding of the drying mechanism. To select a suitable model for describing the drying process of onion slices, drying curves were fitted with five thin-layer drying equations (Eqs 1–5), (Togrul, Pehlivan 2002; Doymaz 2004; Akpinar, Bicer 2005).

$$\text{Exponential}\quad \mathrm{MR} = \exp(-kt) \tag{1}$$

$$\text{Page}\quad \mathrm{MR} = \exp(-kt^{n}) \tag{2}$$

$$\text{Henderson-Pabis}\quad \mathrm{MR} = a\exp(-kt) \tag{3}$$

$$\text{Logarithmic}\quad \mathrm{MR} = a + b\ln(t) \tag{4}$$

$$\text{Power law}\quad \mathrm{MR} = At^{B} \tag{5}$$

where:

MR – moisture ratio (–)

t – time (s)

k, a, b, A – coefficients specific to each model

n, B – exponent specific to each model

The acceptability of the model was determined by the coefficient of determination R^2. In addition to the coefficient of determination, the goodness of fit was determined by various statistical parameters such as reduced mean square of the deviation χ^2, mean bias error E_{MB} and root mean square error E_{RMS}. For quality fit, R^2 value should be higher, close to one, and χ^2, E_{MB} and E_{RMS} values should be lower (Sarsavadia et al. 1999; Togrul, Pehlivan 2002; Demir et al. 2004; Erenturk et al. 2004).

Moisture diffusivity. In drying, diffusivity is used to indicate the flow of moisture out of material. In falling rate period of drying, moisture transfer within the food is mainly by molecular diffusion. Moisture diffusivity is influenced by shrinkage, case hardening during drying, moisture content and temperature of material. The falling rate period of biological materials is best described by Fick's second law of diffusion (Crank 1975). Uniform initial moisture distribution throughout the sample, negligible external resistance to movement and onion slices releasing the moisture from top as well as from bottom surface are assumed. The solution of the above mentioned equation as proposed by Crank (1975) for plane sheet of half thickness (Sharma et al. 2005b) is:

$$\frac{M-M_e}{M_0-M_e}=\frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left[-(2n-1)^2\pi^2\frac{Dt}{L^2}\right] \quad (6)$$

Simplifying this by considering only first term of the series, the equation reduced to:

$$\mathrm{MR}=\frac{M-M_e}{M_0-M}=\frac{8}{\pi^2}\exp\left[-\pi^2\frac{Dt}{L^2}\right] \quad (7)$$

where:

MR – moisture ratio (–)

M_e – equilibrium moisture content (g H_2O/g DM)

M_0 – initial moisture content (g H_2O/g DM)

M – moisture content at time t (g H_2O/g DM)

L – half thickness of slab (0.002 m)

t – time (s)

D – diffusivity coefficient (m^2/s)

Rearranging the above mentioned Eq. (7):

$$\ln(\mathrm{MR})=\ln\left(\frac{8}{\pi^2}\right)-\left(\pi^2\frac{Dt}{L^2}\right) \quad (8)$$

The ln(MR) versus drying time (t) was plotted which would result in straight line and slope of the line would be used to estimate moisture diffusivity during the drying process.

RESULTS AND DISCUSSION

Effect of pre-treatments on drying behaviour of onion slices

Final moisture content of samples dried under different conditions ranged from 5 to 7% dry basis (d.b.). The effect of treatment and drying temperature on time taken to reach the final moisture con-

Table 1. Drying time and effective moisture diffusivity for onion slices

Treatment No.	Temperature (°C)		NaCl concentration (°Bx)	Drying time (min)	Diffusivity (m^2/s)	R^2
	osmotic solution	drying				
1	–	50	–	390	0.78×10^{-10}	0.8827
2	–	60	–	360	0.87×10^{-10}	0.9325
3	–	70	–	315	1.21×10^{-10}	0.9626
4	30	50	10	280	0.83×10^{-10}	0.9662
5	30	50	15	270	0.86×10^{-10}	0.838
6	30	50	20	255	0.91×10^{-10}	0.9374
7	30	60	10	265	0.98×10^{-10}	0.9556
8	30	60	15	255	0.92×10^{-10}	0.9576
9	30	60	20	220	1.09×10^{-10}	0.894
10	30	70	10	250	0.98×10^{-10}	0.9299
11	30	70	15	240	1.14×10^{-10}	0.9265
12	30	70	20	210	1.30×10^{-10}	0.894

R^2 – coefficient of determination

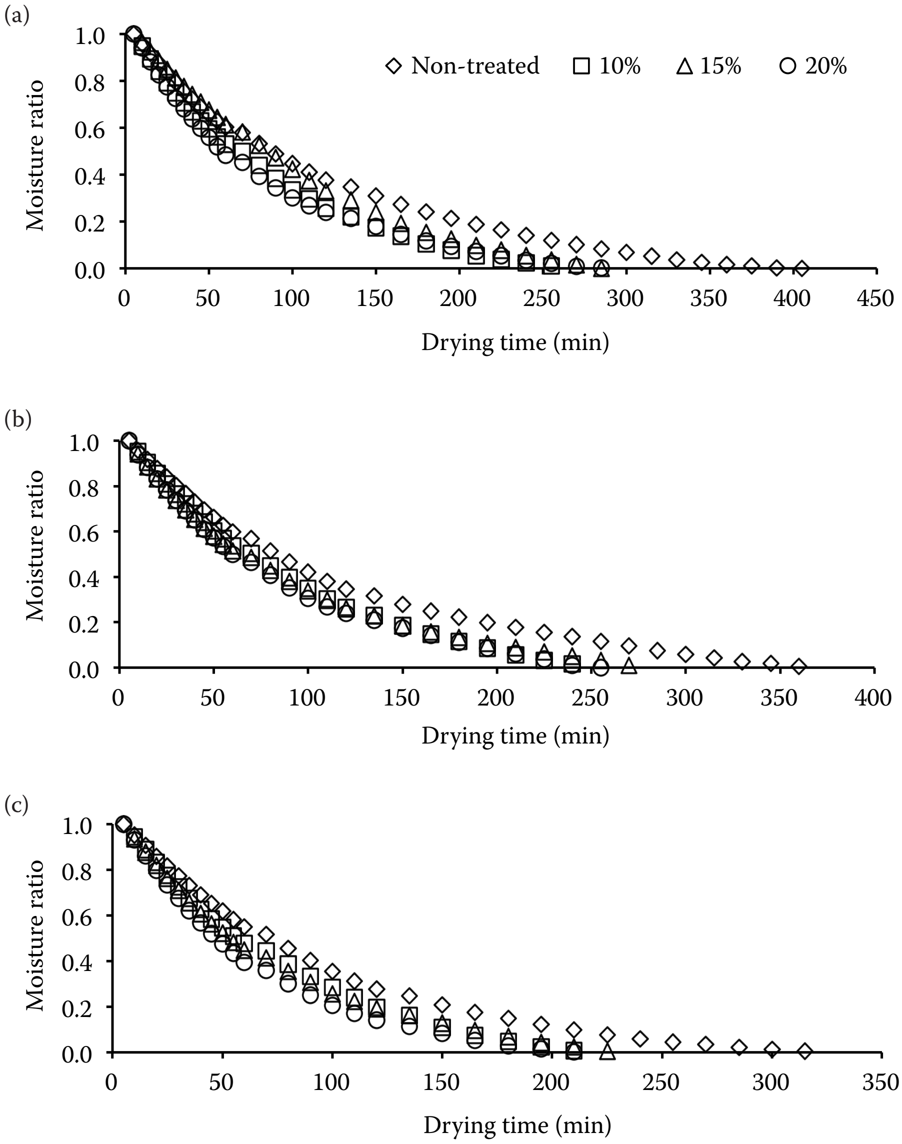

Fig. 1. Effect of pre-treatments on drying time at different drying air temperature (a) 50°C, (b) 60°C and (c) 70°C

tent is presented in Table 1. Drying air temperature has an important effect on drying. At higher temperature, due to the quick removal of moisture, the drying time was shorter. Similar observations were reported for drying of garlic slices (Madamba et al. 1996), onion slices (Sarsavadia et al. 1999), and egg plants (Akpinar, Bicer 2005). In case of onion slices pre-treated with osmotic solution, drying time at all air drying temperatures decreased with the increase in the concentration of NaCl in osmotic solution. The reason of it is that the treatment with the higher NaCl concentration resulted into removal of substantial amount of moisture from the onion slices.

Fig. 1 shows the experimental data (moisture ratio versus drying time) obtained for air at temperatures ranging from 50 to 70°C, and a constant flow rate of 1.5 m/s. As it would be expected, during the initial stages of drying there was a rapid moisture removal from the product, which later decreased with an increase in drying time. From these figures it can be seen that the moisture ratio decreases continually with drying time. As expected, drying air temperatures had much stronger effect on the drying moisture content of onion. The temperature influence was higher at 70°C air temperature. The absence of a constant drying rate period may be due to the thin layer of product that did not provide a constant supply of water for an applied period of time. Continuous decrease in moisture ratio indicates that diffusion has governed the internal mass transfer. This is in agreement with the results of study on onions (Mazza, Lemaguer 1980), lettuce and cauliflower leaves (Lopez et al. 2000) and figs (Piga et al. 2004). Onion slices did not exhibit a constant rate period of drying. The drying occurred

Table 2. Values of model constants and statistical parameters

Treatment No.	Statistical parameters			
	R^2	$\chi^2 \times 10^{-3}$	$E_{MB} \times 10^{-3}$	E_{RMS}
Exponential model				
1	0.8827	0.02184	0.02125	0.01458
2	0.9325	0.00824	0.00800	0.00894
3	0.9626	0.01518	0.01469	0.01212
4	0.9662	0.02580	0.02485	0.01576
5	0.838	0.07616	0.07353	0.02712
6	0.9374	0.01661	0.01604	0.01267
7	0.9501	0.04556	0.04381	0.02093
8	0.9528	0.01565	0.01509	0.01229
9	0.8031	0.07184	0.06918	0.02630
10	0.9259	0.04012	0.03845	0.01961
11	0.9211	0.01735	0.01666	0.01291
12	0.8882	0.03769	0.03612	0.01901
Page model				
1	0.9825	0.00338	0.00319	0.00565
2	0.9897	0.00465	0.00438	0.00662
3	0.9939	0.00494	0.00462	0.00679
4	0.9936	0.00558	0.00517	0.00719
5	0.9869	0.00356	0.00330	0.00575
6	0.9892	0.00686	0.00637	0.00798
7	0.9928	0.00651	0.00601	0.00775
8	0.9915	0.00633	0.00588	0.00767
9	0.9798	0.00619	0.00573	0.00757
10	0.9902	0.00824	0.00756	0.00869
11	0.9899	0.00894	0.00823	0.00907
12	0.9879	0.01026	0.00941	0.00970
Henderson & Pabis model				
1	0.8827	0.05813	0.05499	0.02345
2	0.9325	0.01252	0.01179	0.01086
3	0.9626	0.01936	0.01811	0.01346
4	0.9609	0.05808	0.05378	0.02319
5	0.8294	0.01719	0.16003	0.04000
6	0.9305	0.06567	0.06114	0.02473
7	0.9501	0.02512	0.02318	0.01523
8	0.9528	0.00956	0.00888	0.00942
9	0.8031	0.09337	0.08646	0.02940
10	0.9259	0.05999	0.05499	0.02345
11	0.9804	0.00558	0.00514	0.00717
12	0.8882	0.07930	0.07269	0.02696
Logarithmic model				
1	0.968	0.04626	0.04376	0.02092
2	0.9642	0.05590	0.05262	0.02294
3	0.9655	0.06857	0.06415	0.02533
4	0.9588	0.01554	0.01439	0.01200
5	0.9355	0.02458	0.02288	0.01513
6	0.9761	0.00831	0.00774	0.00880
7	0.9514	0.01871	0.01727	0.01314
8	0.9699	0.01044	0.00970	0.00985
9	0.9668	0.01233	0.01141	0.01068
10	0.9577	0.01770	0.01623	0.01274
11	0.971	0.01149	0.01057	0.01028
12	0.9747	0.01072	0.00982	0.00991
Power law model				
1	0.6009	24.2081	22.8996	0.15133
2	0.6806	9.44003	8.88473	0.09425
3	0.707	15.3818	14.3894	0.11996
4	0.6949	12.2613	11.3530	0.10655
5	0.5502	22.0841	20.5610	0.14339
6	0.668	19.3163	17.9841	0.13410
7	0.6843	9.28092	8.56700	0.09256
8	0.7115	8.58460	7.97141	0.08928
9	0.5387	23.9666	22.1913	0.14897
10	0.6455	14.9387	13.6938	0.11702
11	0.6619	14.2182	13.0808	0.11437
12	0.6179	27.7766	25.4619	0.15957

Table 2 to be continued

R^2 – coefficient of determination; χ^2 – reduced mean square of the deviation; E_{MB} – mean bias error; E_{RMS} – root mean square error

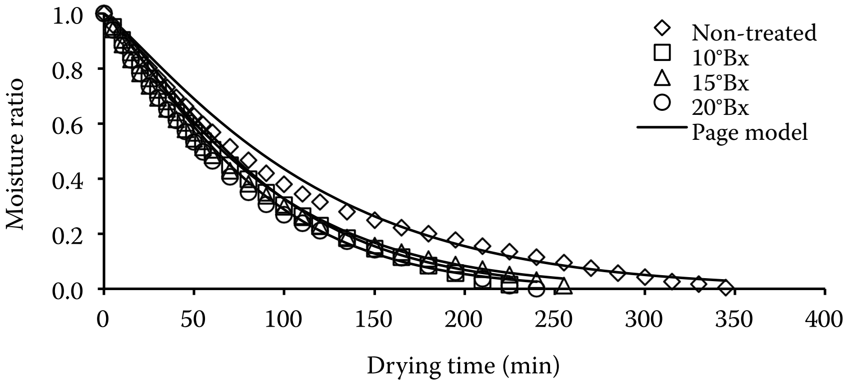

Fig. 2. Experimental moisture ratio versus drying time fitted with the Page model at drying air temperature of 60°C

under falling rate of drying period. Similar results were also reported for the drying studies on plum (Ibitwar et al. 2008) and apricots (Doymaz 2004).

Mathematical modelling of drying curves

The moisture ratio data of pre-treated and non-treated onion slices dried at various temperatures were fitted into the different thin-layer drying models listed above section and the values of (R^2), χ^2, E_{MB} and E_{RMS}, are summarized in Table 2.

It was observed that in all cases, the values of R^2 were greater than 0.90, indicating a good fit (Madamba et al. 1996; Erenturk et al. 2004) except for power law model. However, the Page model gave comparatively higher R^2 values in all the drying treatments (0.9825–0.9939) and also the χ^2 (0.0033–0.01026 × 10^{-3}), E_{MB} (0.00319–0.00941 × 10^{-3}) and E_{RMS} (0.00565–0.00970) values were lower. Hence, the Page model may be assumed to represent the thin-layer drying behaviour of onion slices. Demir et al. (2004) and Goyal et al. (2006) reported a similar result for air-drying of bay leaves and raw mango slices, respectively.

Fig. 2 suggests the experimental moisture ratios fitted with the page model at various air temperatures for onion samples, also Fig. 3 shows a comparison between both observed and predicted moisture values obtained using the Page model, which gave the best fit for the entire onion drying process. This means that the model has very high performance for describing the characteristics of drying curves.

Effective moisture diffusivity

The effective moisture diffusivity, D_{eff}, was calculated using the slopes method (Doymaz 2004; Pathare, Sharma 2006) and its results are given in Table 1. The moisture diffusivity value of food material was affected by moisture content as well as temperature. At lower level of moisture content the diffusivity is less than that of high moisture content. Also it was observed that moisture diffusivity increased with drying air temperature in both non-treated and pre-treated samples (Rahman, Lamb 1991; Pokharkar, Prasad 1998). The moisture diffusivity varied in the range of 0.78 to 1.21 × 10^{-10} m²/s and 0.83 to 1.30 × 10^{-10} m²/s for non-treated and pre-treated onion samples depending on the drying air temperature, respectively. These values are within the general range of 10^{-8} to 10^{-12} m²/s

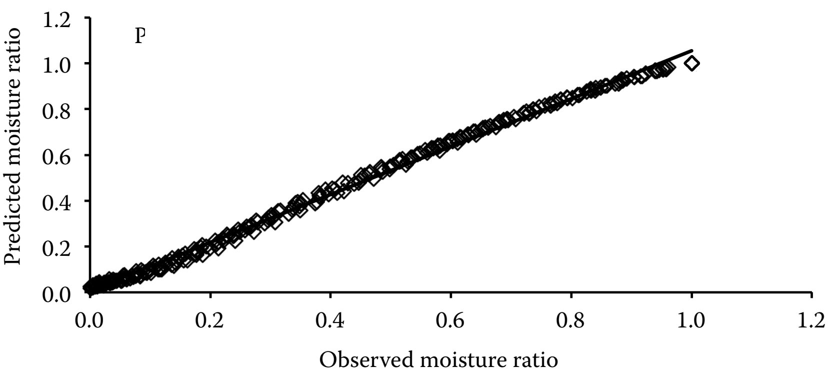

Fig. 3. Comparison of observed and predicted dimensionless moisture ratio values by Page model

for drying of food materials (McMinn, Magee 1999a). The pre-treatment affected the internal mass transfer during drying. Table 1 also indicates that the effective moisture diffusivity during convective dehydration of osmosed samples was higher than untreated samples. Effective moisture diffusivity with osmotic pre-treatment can increase due to loosening of the surface cellular structure and leaching of some soluble components of the external cell layers of onion slices during soaking in osmotic solution. Similar results were reported in apricot cubes (Riva et al. 2005), in melons (Rodrigues, Fernandes 2007) and in pomegranate arils (Mundada et al. 2010).

CONCLUSIONS

The effect of temperature and pre-treatment on drying behaviour of onion slices in tray dryer was investigated in this study. An increase in drying air temperature decreased drying time. Pre-treated onion slices have shorter drying time than the untreated samples. The entire drying process occurred in falling rate period and constant rate period was not observed. Five thin-layer drying equations were investigated for their suitability to describe the drying behaviour of onion slices. The Page model shows the best fit with high values for the coefficient of determination and low χ^2, E_{MB} and E_{RMS} values. The effective moisture diffusivity varied in the range of 0.78 to 1.21×10^{-10} m²/s and 0.83 to 1.30×10^{-10} m²/s for non-treated and pre-treated onion samples depending on the drying air temperature, respectively.

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