Isı Bilimi ve Tekniği Dergisi, 36, 2, 155-162, 2016
J. of Thermal Science and Technology
©2016 TIBTD Printed in Turkey
ISSN 1300-3615

INFLUENCE OF OSMOTIC DEHYDRATION ON DRYING KINETICS OF CARROT

Ahmet KAYA*, Orhan AYDIN and Sevgi KOLAYLI*****
[*]Department of Mechanical Engineering, Kahramanmaras Sutcu Imam University
46100 Kahramanmaras, TURKEY
[**]Department of Mechanical Engineering, Karadeniz Technical University,
61080 Trabzon, TURKEY
[***]Department of Chemical Engineering, Karadeniz Technical University,
61080 Trabzon, TURKEY
**corresponding author* Tel: +90 (344) 280 1694; Fax: +90 (344) 280 1602; e-mail: ekaya38@gmail.com

(Geliş Tarihi: 01.10.2014, Kabul Tarihi: 27.06.2016)

Abstract: In this study, effects of osmotic dehydration (OD) on drying kinetics of carrot slices are investigated. Carrot slices are osmotically dehydrated with three type sucrose plus salt mixture solutions at 35^{o}C, 45^{o}C and 55^{o}C. After that non-treated and pre-treated samples are dried in a convective dryer at the same temperatures, a constant air velocity (0.3 m/s) and a constant relative humidity (15%) until the equilibrium moisture content is achieved. A simplified model based on the solution of Fick's Law is used to estimate effective diffusion coefficients for the non-treated and pretreated carrot slices. The experimental moisture data are then fitted to some models available in the literature, mainly the Henderson and Pabis model, the Lewis model and the two-term exponential model and, a good agreement is observed.
Keywords: Convective drying, osmotic dehydration, carrot, diffusion coefficient

HAVUCUN KURUMA KİNETİĞİ ÜZERİNE OZMOTİK DEHİDRASYONUN ETKİSİ

Özet: Bu çalışmada, havuç dilimlerinin kuruma kinetiğine üzerine ozmotik dehidrasyonun (OD) etkisi incelenmiştir. Havuç dilimleri, 35^{o}C, 45^{o}C ve 55^{o}C'de üç tip şeker-tuz karışımı çözeltilerde ozmotik dehidrasyona tabii tutulmuştur. Daha sonra, işleme tabii tutulan ve tutulmayan örnekler, aynı sıcaklıklarda sabit hız (0.3 m/s) ve sabit bağıl nemde (%15) ürün denge nem içeriğine ulaşıncaya kadar bir konvektif kurutucuda kurutulmuşlardır. İşleme tabi tutulan ve tutulmayan havuç dilimlerinin efektif difüzyon katsayılarını belirlemede için Fick difüzyon denkleminin çözümüne dayalı basitleştirilmiş model kullanılmıştır. Deneysel nem verileri daha sonra literatürde mevcut bulunan Henderson ve Pabis, Lewis ve iki-terimli eksponansiyel gibi bazı modellere yerleştirilmiş iyi bir uyum sağlanmıştır.
Anahtar kelimeler: konvektif kurutma, ozmotik dehidrasyon, havuç, difüzyon katsayısı

Nomenclature

A	Drying coefficient
b	Drying coefficient
Deff	Effective diffusion coefficient, (m^2/s)
DR	Drying rate, (kg H_2O)/ (kg d.m. h)
e.r.h	Equilibrium relative humidity (%)
k	Drying constants, 1/s
k_0	Drying constants, 1/s
k_1	Drying constants, 1/s
L	Thickness of the carrot slices, m
M	Moisture content at t, (kg H_2O/ kg d.m.)
M_e	Equilibrium moisture content, (kg H_2O/ kg d.m.)
M_i	Initial moisture content, (kg H_2O/kg d.m.)
MR	Moisture ratio, ($MR = \frac{M - M_e}{M_i - M_e}$)
R^2	Coefficient of determination
T	Temperature, °C
t	Time, h
U	Velocity, m/s
φ	Relative humidity

INTRODUCTION

Carrot (Daucus carota L.) is known for its nutrient contents viz. carotene and carotenoids besides appreciable amounts of vitamins B1, B2, B6 and B12 and minerals. Out of various methods of extending the shelf life of perishable crops, osmotic dehydration is one of the simple and inexpensive processes (Singh and Gupta, 2007).

Due to physical, chemical and biochemical changes during drying, quality degradation is a major concern in the selection, design and operation of a food drier (Mujumdar, 1997).

Dehydration of foodstuffs by immersion in osmotic solutions previous to convective air-drying seems to improve the quality of the final product since it prevents oxidative browning and loss of volatile flavoring constituents, decreases the fruit acidity (Del Vale at., 1973). It also decreases structural collapse during air-drying (Del Vale at, 1973; Lenart, 1996; Simal at, 1997) minimizes drying color losses (Nsonzi and Ramaswamy, 1998) and reduces nutrient losses, e.g. lycopene in vacuum-dried tomatoes (Shi at, 1999; Garcia at, 2007)

Osmotic dehydration (OD) of fruits and vegetables is based on their immersion in an aqueous concentrated solution containing one or more solutes. This process involves the simultaneous flow of water and solutes. Water and food solutes diffuse from the food to the concentrated solution and solution solutes from the osmotic solution into the food. Solute transfer is usually limited due to differential permeability of cellular membranes (Bildweel, 1979). Consequently, more water transfer than solute transfer characterizes this process.

The effects of osmotic pre-treatment on drying kinetics have been investigated by several authors. Singh and Gupta (Singh and Gupta, 2007) established the convective dehydration kinetics of un-osmosed and pre-osmosed carrot cubes at different air temperature and estimated effective moisture diffusivity using the analytical solution of Fick's Law. Sankat et al. (Sankat at, 1996) investigated the drying kinetics of banana slices which were previously osmosed in sucrose solutions and fresh slices and determined moisture diffusivities for fresh and osmosed samples. Park et al. (Park at, 2002) studied the drying behavior of fresh and osmosed pears and determined moisture diffusivities of them.

Doymaz (Doymaz, 2006) examined the drying behavior of fresh and pretreatment black grapes and evaluated moisture diffusivities for different osmotic solutions.

Tsamo et al. (Tsamo vd, 2005) determined the drying kinetics, drying constant and moisture diffusivity for fresh and osmotically dehydrated onion slices and tomato. Garcia et al.[9] investigated kinetics of osmotic dehydration and effects of sucrose impregnation on thermal air-drying of pumpkin slices and estimated effective diffusion coefficients during OD and air-drying using the Fick's Law. Moreiar et al. (Moreira at, 2007) established experimentally the low-temperature air-drying kinetics of chestnuts previously treated osmotically with sucrose and glucose solutions and determined moisture diffusivities for different temperature and osmotic solutions.

Tsamon et al. (Tsamo at, 2006) determined the drying constants of onion slices and tomato fruits, fresh and osmotically dehydrated in sugar, salt or mixed salt and sugar solutions.

The purpose of this work is to estimate drying behavior of non-treated and osmosed carrot slices and to determine effective diffusion coefficients.

MATERIALS AND METHODS

Experimental Equipment

Experiments were conducted in a lab-scale convective air-dryer as shown in Fig. 1. The experimental setup consists of fan, heater, air conditioner, humidifier, fresh air damper, air exit damper, mixing damper, drying tray, load cell, data acquisition and computer. The convective dryer is equipped with controllers for controlling the temperature, airflow velocity and relative humidity. The rectangular-sectioned channel dimensions are 50 cm x 25 cm with 4000 cm length. In order to prevent the heat loss to the environment, the channels are insulated. The mass flow rate of the drying air is regulated by a fan driven by a variable speed motor to obtain air velocities in the range from 0.3 to 0.9 m/s at the entrance of the channels. Drying basket with a holding area of 40 cm x 20 cm is included in the channels. The test samples of the carrot slices (thickness L=7 mm), weighing about 500 g are placed in the drying basket.

The initial and equilibrium moisture content of treatment and non-treatment carrot are determined using the OHAUS MB45, Switzerland infrared moisture analyzer. During the experiments, the temperature changes and sample weight were measured using microprocessor thermometers (model HH21, Omega, USA and accuracy 0–400 ± 0.1^{o}C) and load cells (model Lama, Esit, Turkey and accuracy 10,000 ± 0.01 g), respectively. All data collected were recorded in every 2.5 min for temperature and 30 min for moisture using a data logger interfaced to a personal computer. Furthermore, the velocity in the drying channel was continuously measured with anemometers (hot-wire and vine type) (model 4204AM (hot-wire), 4202AM (vine), Lutron HT, Taiwan with an accuracy of 0.2–20.0 ± 0.05 m/s, while the relative humidity in the test section was measured using a humidity/temperature meter (4204AM model, Lutron HT, Taiwan with accuracy of 10–95 ± 1%).

Osmotic Dehydration

Carrot slices were weighed, placed in four mesh baskets and immersed in three type sucrose plus salt solutions; i) 5%NaCl+50^{o}Brix sucrose and dipping time 2 h (OD-I), ii) 5%NaCl+50^{o}Brix sucrose and dipping time 4 h (OD-II) and iii) 15%NaCl+50^{o}Brix sucrose and dipping time 2 h (OD-III). The OD system consisted of a jacketed stainless steel vessel containing 15 kg of aqueous sucrose solution continuously stirred and maintained at 35^{o}C, 45^{o}C and 55^{o}C by circulation of thermostatically controlled water in the jacket.

Two baskets were prepared for each process time. Syrupto-fruit ratio was approximately 15:1. After the pre-established contacting period, the samples were removed, their surfaces were cleaned with wet tissue, blotted with absorbing paper, and weighed.

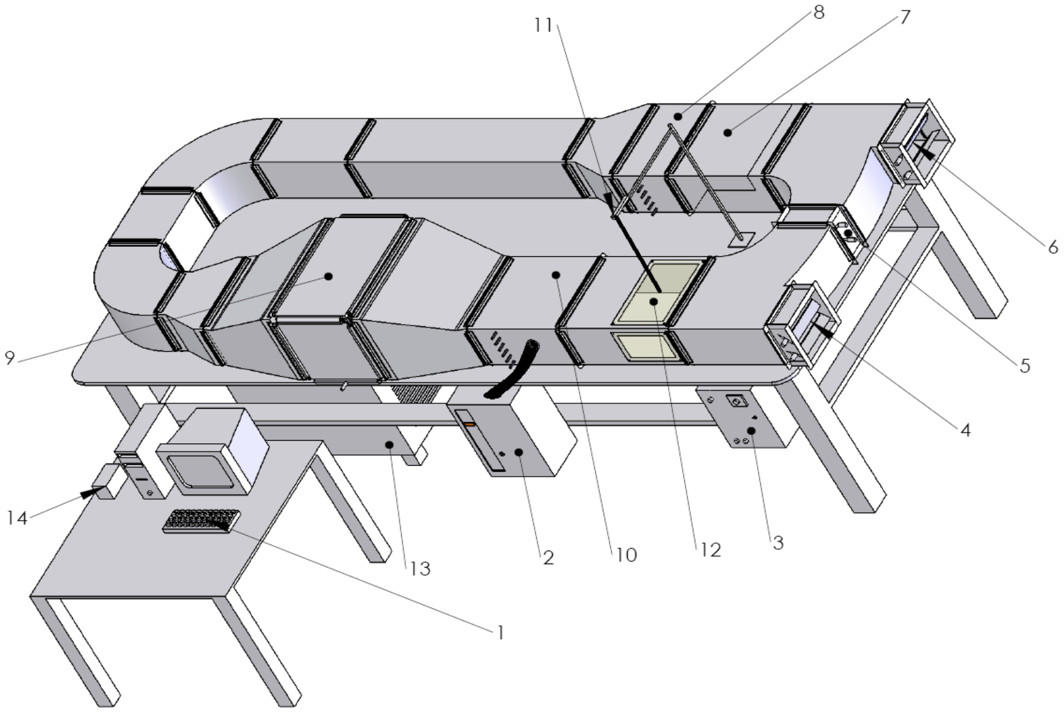


Figure 1. The schematic of the experimental setup.
1- Computer, 2- Humidifier, 3-Control panel, 4- Air out damper, 5- Mixing damper, 6- Fresh air damper, 7- Fan, 8- Heater, 9- Condenser, 10- Heater, 11- Loadcell, 12- Test section, 13-Condenser unit (compressor, fan), 14-Data acquisition system

Theoretical Analyses

The diffusion coefficient can be determined from the widely used equation given as follows (Crank, 1975):

$$MR = \frac{M - M_e}{M_i - M_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-\frac{(2n+1)^2}{L^2} D_{eff}\, t \right] \quad (1)$$

where M_e is the equilibrium moisture content (kg H_2O/(kg d.m.)) determined from Table 1, M_i is the initial moisture content (kg H_2O/(kg d.m.)), L is the thickness of the slice (m), D_{eff} is the moisture diffusivity (m^2/s), t is the drying time (h).

There are many statistical-based expressions correlating experimentally obtained *MR* values in terms of *t* in the existing literature. Generally, these correlations remain case-dependent, each suggesting coefficients varying from product to product. Therefore, they cannot be generalized. Moreover, many of these expressions just fitting curves for *MR* versus *t* have a form not consistent with the analytical solution of the problem (Kaya vd, 2007-a; Kaya vd., 2007-b; Kaya vd, 2007-c).Therefore, only the models consistent with the analytical solution of the problem were considered in this study, which were shown in Table 2.

Table 1. Initial and equilibrium moisture content (kg H_2O/kg d.m.) for different temperatures for the non-treated and treated carrot slices.

	Parameter	T=35^{o}C	T=45^{o}C	T=55^{o}C
1	Non-treatment	M_i=6.77	M_i=6.77	M_i=6.77
		M_e=0.095	M_e=0.052	M_e=0.028
2	OD-I (%5 NaCl + sucrose 50Brx^o, dipping time 2 h)	M_i=4.61	M_i=3.97	M_i=3.02
		M_e=0.063	M_e=0.015	M_e=0.0095
3	OD-II (%5 NaCl + sucrose 50Brx^o, dipping time 4 h)	M_i=2.56	M_i=2.026	M_i=1.55
		M_e=0.027	M_e=0.0097	M_e=0.0086
4	OD-III (%15 NaCl + sucrose, dipping time 2 h)	M_i=3.23	M_i=2.99	M_i=2.071
		M_e=0.069	M_e=0.023	M_e=0.016

Table 2. Thin-layer drying models considered.

Model name	Equation	Reference
Lewis	MR=exp(-kt)	Mujumdar (Mujumdar, 1987)
Henderson and Pabis	MR=a exp(-kt)	Henderson and Pabis (Henderson at, 1961)
Two term exponential	MR=a exp(-k_0t)+b exp(-k_1t)	Henderson (Henderson, 1974)

The drying rate, DR, of the non-treated and pretreated carrot slices during drying process can be determined using the following equations:

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \qquad (2)$$

RESULTS AND DISCUSSION

Effect of Osmotic Pre-Treatment on Convective Dehydration Kinetics

Products to be dried were immersed into solution at 35°C, 45°C and 55°C. Then, their drying behaviors were investigated in a convective dryer at the same temperatures, respectively.

The measured values of the initial moisture content (M_i) and the equilibrium moisture content (M_e) at the end of the drying process have been given in Table 2. The difference in initial moisture content of osmotic pretreatment products reflects the varying degrees of water loss during the osmotic pretreatment and it indicates reduction of residual water content with increasing the osmotic treatment time and the rate of the salt in the mixture. Also, it is shown that in Table 2, the equilibrium moisture content (M_e) decreases with an increase in the pre-osmotic time and the rate of the salt in the solution.

The total convective dehydration times of samples at 35, 45 and 55°C, when dried to final moisture content, are as given in Table 3. At 35°C, the total convective dehydration time was 1260 min for non-treated samples while it was 1290, 1230 and 1320 min for the samples of the pre-treatment with OD-I, OD-II and OD-III, respectively.

Therefore, the osmotic pre-treatment added approximately 30 min and 60 min in OD-I and OD-III, respectively, while it shortened approximately 30 min in OD-II with respect to the convective dehydration time when compared to the non-treated carrot slices at 35°C of the drying air temperature.

Table 3. Total drying time for treatment and non-treatment carrots slices.

Temperature (°C)	Drying time (min)			
	Non-treatment	OD-I	OD-II	OD-III
35	1260	1290	1230	1320
45	1050	1050	960	1050
55	900	900	810	900

The reduction in the convective dehydration time may only be possible if the osmo-convective drying has to be performed to prepare intermediate moisture foods having high final moisture content. Among the pre-treated samples, lower convective dehydration time was observed for the samples osmosed in OD-III than those osmosed in OD-I and OD-II. This might be due to different modes and extents of sample impregnation with osmotic solutes of different molecular size during the osmotic dehydration process.

The resistances imparted by infused sucrose and NaCl salt to moisture out flow during convective dehydration were different, because the sucrose (having high molecular weight) accumulates in a thin subsurface layer resulting in surface tissue compaction (an extra mass transfer barrier), while NaCl salt (having low molecular weight) penetrates the osmosed tissue to a much greater depth (Singh and Gupta, 2007; Lenart and Flink, 1984).

Effect of Drying Air Temperature on Drying Kinetics

Drying process started when outside air is brought to the set conditions. Experiments were conducted for a constant velocity (0.3 m/s) and a constant relative humidity (15%) at 35, 45 and 55°C. Drying was continued until the equilibrium moisture content is reached. Experiments were repeated at least three times for any studying range in order to validate the results obtained.

Variations of the moisture content with the drying time t for varying values of the drying air temperature have been studied for the pretreated (OD-I, OD-II and OD-III) and non-treated carrot samples. Figures 2 and 3 show effect of the air temperature on the moisture content variation with time at φ=15% and U=0.3 m/s for the non-treated and the pretreated carrot samples (OD-I, OD-II and OD-III). As seen from the figures, increasing the air temperature decreases the total drying time since heat transfer was increased. Increasing T from 35°C to 55°C for non-treated, OD-I, OD-II and OD-III have lead to a decrease of 28.6%, 31.8%, 34.14% and 31.8% in the total drying time, respectively.

The variation of the drying rate, *DR*, with the drying time, *t* obtained from Eq. (2) is shown in Figs. 4 and 5 for varying temperature of the drying air for the non-treated and the pretreated products. Due to the moisture diffusion process, the drying rate decreased with time.

Carrot slices did not exhibit a constant rate period of drying (Figs. 4 and 5). The entire drying process occurred in the falling rate period, during which internal molecular diffusion is the predominant mechanism of mass transfer. From Fig.5a, it can be seen that the drying rate is also higher for higher air temperatures. For higher values of the moisture content, increase in the drying temperature resulted in higher drying rate. This can be explained by the increasing temperature difference between the drying air and the product and in follows water migration (Kaya at, 2008).

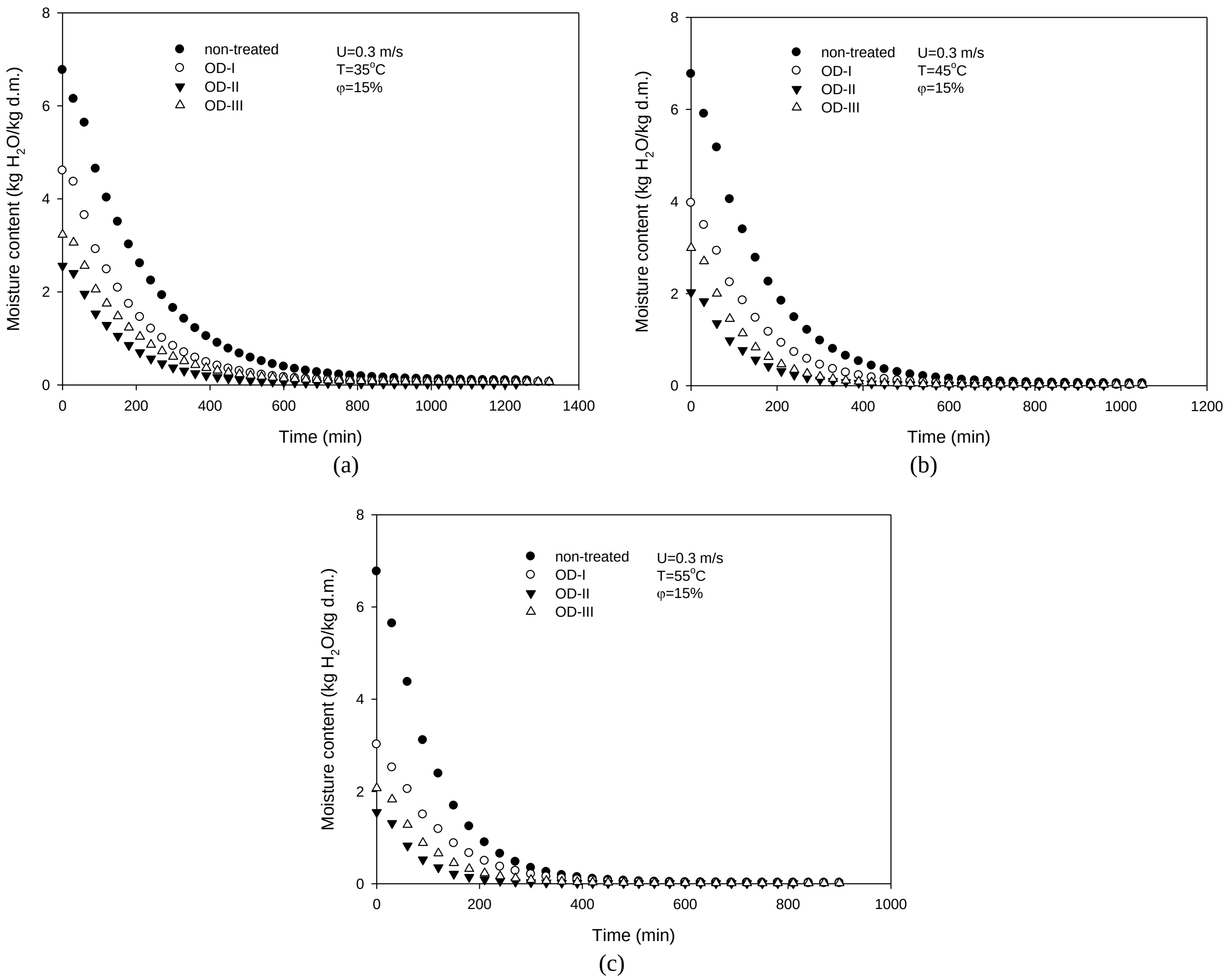


Figure 2. The variation of the moisture content with t for the non-treated samples (OD-I, OD-II and OD-III) at U=0.3 m/s and φ=15% (a) T=35°C, (b) T=45°C, (c) T=55°C.

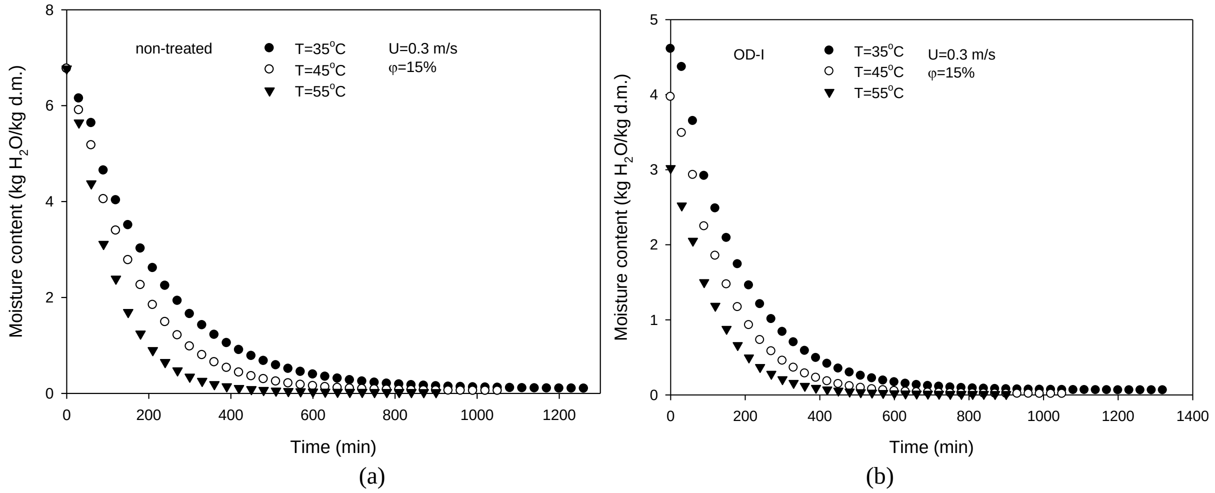
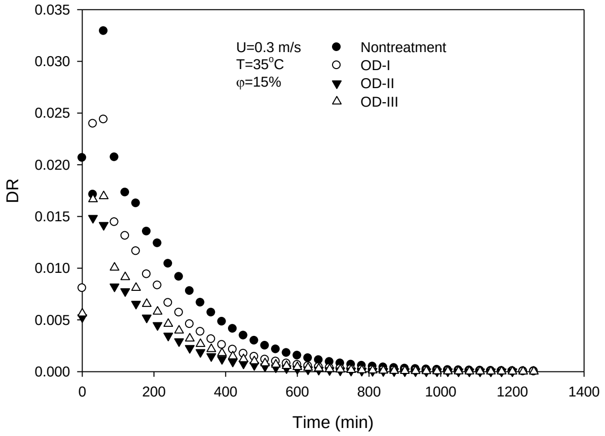
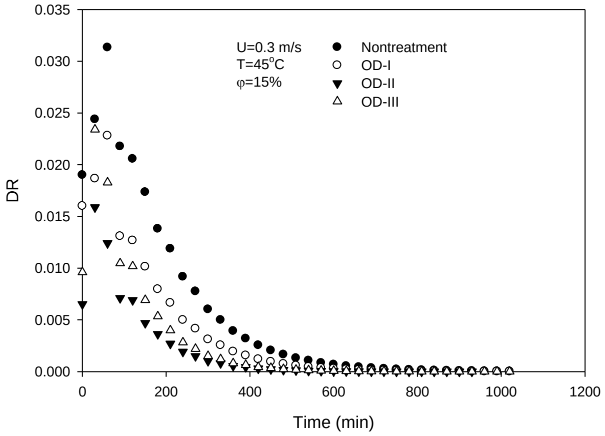


Figure 3. The variation of the moisture content with t for various T at U=0.3 m/s and φ=15% for the non-treated sample (a) and the OD-I sample (b).

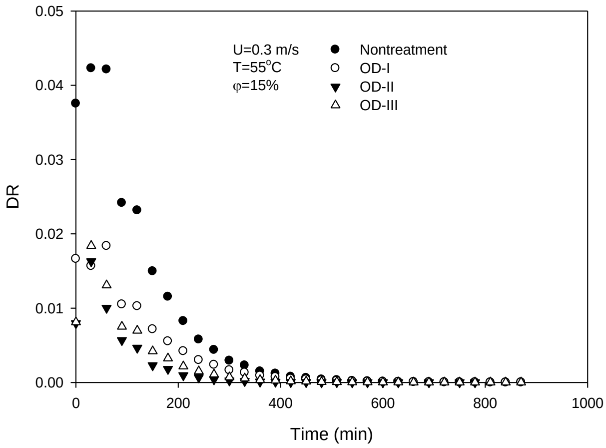
Thin-layer drying models presented in Table 2 were used to describe the drying behavior of non-treated and pre-treated carrot slices. The results of the statistical computations carried out to evaluate three drying models when applied to the experiment are presented in Table 4. The values of R^2, is also included in Table 4. In all cases, the values of R^2 for the models were greater than an acceptable threshold of 0.90, giving a credit to the validity of the models used. As shown, for all the cases studied, the two-term exponential model has shown a better fit to the experimental drying data as compared to the other models considered as shown Fig.6.



(a)



(b)

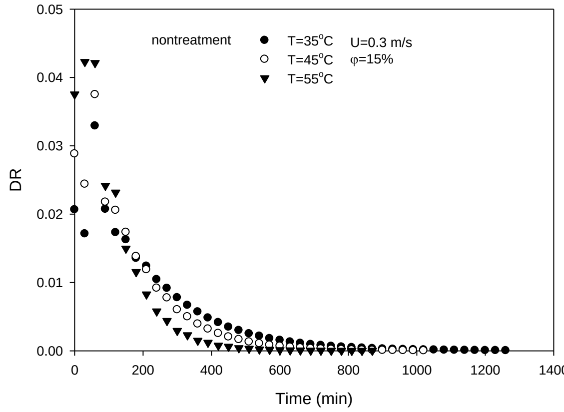


(c)

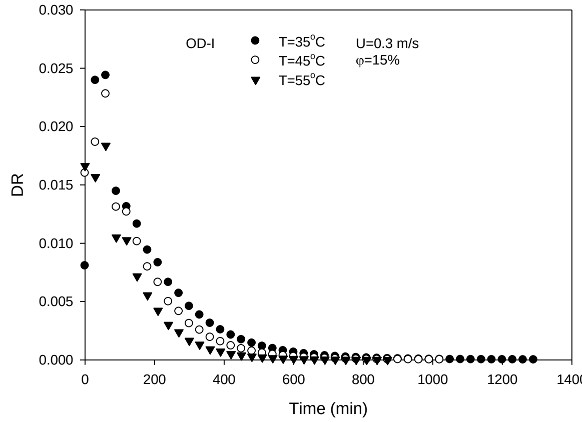
Figure 4. The variation of the DR with t for the non-treated samples (OD-I, OD-II and OD-III) at U=0.3 m/s and φ=15% (a) T=35°C, (b) T=45°C, (c) T=55°C.

Diffusion Coefficient

For long drying times, only the first term (n=1) of the series (Eq. 1) is considered as solution and the moisture diffusivity, D_{eff}, can be easily predicted using the linear regression analyses (see Table 5). Increasing the air temperature increases the value for D_{eff} for all the cases tested. The effective diffusivity values of the dried samples were varied between 4.485-12.071x10^{-10} m^2/s. These values are in fact consistent with those existing in the literature, e.g. 7.81–10.6x10^{-10} m^2/s for air drying of osmosed and fresh carrot cubes [1]; 1.59-8.12 x10^{-10} m^2/s for hot air drying of osmosed pear (Park at, 2002); 3.82-12.81x10^{-10} m^2/s for hot-air drying of osmosed black grapes (Doymaz, 2006) and 1.28-3.3x10^{-10} m^2/s for hot air drying of osmosed chestnuts (Moreira at, 2007).



(a)



(b)

Figure 5. The variation of the DR with t for various T at U=0.3 m/s and φ=15% for the non-treated sample (a) and the OD-I sample (b).

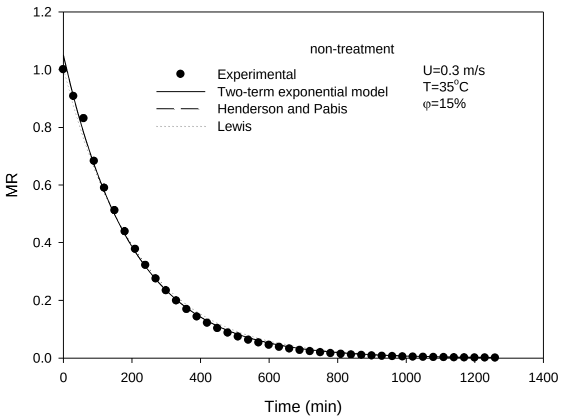


Figure 6. Experimental and predicted moisture ratio

Table 4. Drying coefficient for the treated and non-treated carrot slices

		Air condition					Air condition					Air condition			
Parameters	Two-term exp. model	T=35°C	T=45°C	T=55°C	R^2	Henderson and Pabis Model	T=35°C	T=45°C	T=55°C	R^2	Lewis model	T=35°C	T=45°C	T=55°C	R^2
Non-treated	a	0.5432	0.5414	0.5406	0.9976	a	1.0510	1.0493	1.0474	0.9977	k(1/min)	0.0047	0.0062	0.0090	0.9957
	k_0(1/min)	0.0050	0.0065	0.0094		k (1/min)	0.0050	0.0065	0.0094						
	b	0.5078	0.5079	0.5068											
	k_1(1/min)	0.0050	0.0065	0.0094											
OD-I	a	0.5575	0.5448	0.5366	0.9964	a	1.0698	1.0533	1.0452	0.9964	k(1/min)	0.0056	0.0068	0.0082	0.9930
	k_0(1/min)	0.0059	0.0071	0.0085		k (1/min)	0.0059	0.0071	0.0085						
	b	0.5123	0.5085	0.5087											
	k_1(1/min)	0.0059	0.0071	0.0085											
OD-II	a	0.5579	0.5560	0.5548	0.9958	a	1.0720	1.0707	1.0682	0.9958	k(1/min)	0.0061	0.0083	0.0118	0.9923
	k_0(1/min)	0.0066	0.0089	0.0125		k (1/min)	0.0066	0.0089	0.0125						
	b	0.5128	0.5160	0.5134											
	k_1(1/min)	0.0066	0.0089	0.0125											
OD-III	a	0.5575	0.5574	0.5560	0.9964	a	1.0719	1.0712	1.0699	0.9964	k(1/min)	0.0056	0.0083	0.0096	0.9930
	k_0(1/min)	0.0059	0.0089	0.0102		k (1/min)	0.0059	0.0089	0.0102						
	b	0.5123	0.5138	0.5160											
	k_1(1/min)	0.0059	0.0089	0.0102											

Table 5. Diffusion coefficients for various temperatures.

D_{eff}x10^{10} m^2/s						
	T=35°C	R^2	T=45°C	R^2	T=55°C	R^2
Nontreated	4.485	0.9987	5.954	0.9988	8.469	0.9992
OD-I	5.367	0.9991	6.461	0.9990	7.898	0.9988
OD-II	5.636	0.9993	8.230	0.9992	12.071	0.9989
OD-III	5.065	0.9990	8.088	0.9989	9.374	0.9993

CONCLUSIONS

The following conclusions can be summarized from the study:The effects of the drying conditions and the osmotic dehydration on the total drying time were studied. Increasing the temperature decreases the total drying time both for the treated and non-treated samples. Increasing T from 35°C to 55°C for the non-treated and treated samples have lead to a decrease of 28.6%, 31.8%, 34.14% and 31.8% in the total drying time for non-treated, OD-I, OD-II and OD-III, respectively.The two-term exponential and the Henderson and Pabis models provided the best fit for the drying curves of both the treated and non-treated carrot slices. Effective moisture diffusivity of carrot was found to be range between 4.485x10^{-10} m^2/s and 12.071x10^{-10} m^2/s.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support provided by Karadeniz Technical University Research Fund under Grant No 2004.112.003.01 and the Turkish Republic Prime Ministry State Planning Organization (DPT) under grant no 2003K120750. The second author of this article is also indebted to the Turkish Academy of Sciences (TUBA) for the financial support provided under the Programme to Reward Success Young Scientists (TUBA-GEBIT).

REFERENCES

Bildweel, R.G.S., 1979, Plant Physiology; *Macmillan Publishing*, New York.

Crank, J., 1975, *The Mathematics of Diffusion*; Oxford Univ. Pres: London.

Del Vale, J.M., Cuadros, T.R.M. and Aguilera, J.M., 1998, Glass transition and shrinkage during drying and storage of osmosed apple pieces, *Food Res. Int.*, 31(3), 191–204.

Doymaz, I., Drying kinetics of black grapes treated with different solutions, *J. Food Eng.*, 76, 212-217.

Garcia, C.C., Mauro, M.A. and Kimura, M., Kinetics of osmotic dehydration and air-drying of pumpkins (Cucurbita moschata), *J. Food Eng.*, 82, 284–291.

Henderson, S.M. and Pabis, S., 1961, Grain drying theory I. Temperature effect on drying coefficient, *J. Agric. Eng. Res.*, 6(3), 169 174.

Henderson, S.M., 1974, Progress in developing the thin layer drying equation, *Transactions of the ASAE*, 17, 1167–1172.

Kaya, A., Aydın, O. and Dincer, I., 2008, Experimental and numerical investigation of heat and mass transfer during drying of Hayward kiwi fruits (Actinidia Deliciosa Planch), *J. Food Eng.*, 88, 323 330.

Kaya, A., Aydın, O. and Demirtaş, C., 2007-a, Drying kinetics of red delicious apple, *Biosystems Eng.*, 96, 517–524.

Kaya, A., Aydın, O. and Demirtaş, C., 2007-b, Concentration boundary conditions in the theoretical analysis of convective drying process, *J. Food Process Eng.*, 30, 564–577.

Kaya, A., Aydın, O., Demirtaş, C. and Akgun, M., 2007-c, An experimental study on the drying kinetics of quince, *Desalination*, 212, 328–343.

Lenart, A. and Flink, J.M., 1984, Osmotic concentration of potato. I. Criteria for the end point of the osmosis process , *J. Food Technol.*, 19, 45–63.

Lenart, A., 1996, Osmo-convective drying of fruits and vegetables: technology and application, *Drying Tech.*, 14(2), 391–413.

Moreira, R., Chenlo, F., Chaguri, L. and Oliveira, H., 2007, Drying of Chestnuts (Castanea sativa Mill.) after Osmotic Dehydration with Sucrose and Glucose, *Drying Tech.*, 25, 1837–1845.

Mujumdar, A.S., 1987, *Handbook of Industrial Drying*; Marcel Dekker, New York.

Mujumdar, A.S., 1997, *Drying fundamentals. In Industrial Drying of Foods*; Baker, C. G. J. (Ed.); *Blackie Academic and Professional: London*, pp. 7-30.

Nsonzi, F. and Ramaswamy, S., 1998, Quality evaluation of osmoconvective dried blueberries, *Drying Technol.*, 16(3-5), 705–723.

Park, K.J., Bin, A. and Brod, F.P.R., Drying of pear d'Anjou with and without osmotic dehydration, *J. Food Eng.*, 56, 97–103.

Ponting, J.D., 1973, Osmotic dehydration of fruits–recent modification and applications, *Process Biochem.*, 8, 18–20.

Sankat, C.K., Castaigne, F. and Maharaj, R., 1996, The air drying behaviour of fresh and osmotically dehydrated banana slices, *Int. J. Food Sci. Technol.*, 31(2), 123-135.

Shi, J., Le Maguer, M., Kakuda, Y., Liptay, A. and Niekamp, F., 1999, Lycopene degradation and isomerization in tomato dehydration. *Food Res. Int.*, 32,15-21.

Singh, B. and Gupta A.K., 2007, Mass transfer kinetics and determination of effective diffusivity during convective dehydration of pre-osmosed carrot cubes, *J. Food Eng.*, 79, 459 470.

Simal, S., Deya, E., Frau, M. and Rossello, C., 1997, Simple modelling of air drying curves of fresh and osmotically pre-dehydrated apple cubes. *J. Food Eng.*, 33, 139–150.

Tsamo, C.V.P., Bilame, A.F., Ndjouenkeu, R. and Nono, Y.J., 2005, Study of material transfer during osmotic dehydration of onion slices (Allium cepa) and tomato fruits (Lycopersicon esculentum). LWT – *Food Sci. Technol.*, 38, 495–500.

Tsamo, C.V.P., Bilame, A.F. and Ndjouenkeu, R., 2006, Air drying behaviour of fresh and osmotically dehydrated onion slices (allium cepa) and tomato fruits (lycopersicon esculentum), *Int. J.Food Prop.*, 9, 877–888.