Osmotically dehydrated microwave vacuum drying of carrots

V. Changrue[1] and V. Orsat[2]*

[1]Agricultural Engineering, Chiang Mai University, Chiang Mai, Thailand; and [2]Department of Bioresource Engineering, Macdonald Campus, McGill University Ste. Anne-de-Bellevue, Québec, Canada, H9X 3V9. *Email: valerie.orsat@mcgill.ca.

Changrue, V. and V. Orsat. 2009. **Osmotically dehydrated microwave vacuum drying of carrots**. Canadian Biosystemes Engineering/Le génie des biosystèmes au Canada. 51: 3.11–3.19 Osmotic dehydration prior to drying was able to remove free water, which accounts for around 50% of the product's moisture. The combination of osmotic and microwave vacuum drying was investigated. The advantage of microwave vacuum drying is that it provides faster drying times with a low-temperature process. Since solid gain from osmotic agents might cause a decrease in diffusivity of the osmotically dehydrated product and lower qualities of dried product, it is important to know the effects of osmotic treatment prior to microwave vacuum drying. Two levels of microwave input power (1 and 1.5 W/g) and three power modes (continuous, 45 s on/15 s off and 30 s on/30 s off) were studied at an absolute pressure of 8 kPa for the microwave vacuum drying of carrots. Drying kinetics, energy consumption, and quality in terms of water activity, shrinkage, rehydration capacity, color characteristics, and sensory evaluation were studied. Empirical models were established to fit the observed data. In general, osmotic dehydration was able to decrease drying time and energy consumption. Less shrinkage and improved appearance were the advantages in terms of quality. Page's model showed the best fit among the tested models. **Keywords:** microwave vacuum, osmotic, carrots.

La déshydratation osmotique précédant le séchage a permis d'extraire l'eau libre qui représente près de 50% de l'humidité du produit. Le jumelage de la déshydratation osmotique et du séchage microonde sous-vide a été étudié. L'avantage du séchage microonde sous-vide est qu'il permet un temps de séchage très rapide et ce à basse température. Puisque le gain en matières solides provenant de la solution osmotique peut réduire la diffusivité hydraulique du produit déshydraté par osmose et par conséquent en diminuer la qualité lors du séchage de finition, il est important de connaître les effets des traitements osmotiques précédant le séchage microonde sous-vide. Deux niveaux de puissance microonde (1 et 1.5 W/g) et trois niveaux d'application de l'énergie (en continu, ou pulsé 45 s ouvert/15 s fermé et 30 s ouvert/30 s fermé) ont été étudiés à la pression absolue de 8 kPa pour le séchage microonde sous vide de la carotte. La cinétique du séchage, la consommation énergétique, et la qualité des carottes en termes de l'activité de l'eau, du rétrécissement, de la capacité de réhydratation, de la couleur et de l'évaluation sensorielle ont été étudiés. Des modèles empiriques ont été développés pour représenter le plus précisément les données observées. En général, la déshydratation osmotique a pu réduire le temps de séchage et la consommation d'énergie. Une diminution du rétrécissement et une amélioration de l'apparence ont été observées. Le modèle de Page a été le meilleur des modèles testés. **Mots clés:** microonde sous vide, osmose, carottes.

INTRODUCTION

The simplest objective of drying is to remove moisture to a level that prevents microbial growth, in order to extend shelf-life, while maintaining product quality. Today it is necessary to maintain the nutritional value of food products with minimal energy consumption, which cannot be easily achieved by a single drying technique as was done in the past.

Carrot (*Daucus carota* L.) is a good source of β-carotene, thiamine, iron, vitamin C and sugar. It is classified as a commercially significant vegetable. Drying of carrots has been studied in a number of ways, e.g., sun drying (Mulet et al. 1993), solar drying (Ratti and Mujumdar 1997), convective air drying in a tunnel or on a conveyor (Grabowski and Marcotte 2003), convective microwave drying (Prabhanjan et al. 1995), microwave vacuum drying (Cui et al. 2004) and freeze drying (Lin et al. 1998). Among them, convective hot air is the most widely used technology for carrots, with an air temperature of around 70°C and final moisture content of about 4–8% (w.b.) (Grabowski and Marcotte 2003). To achieve the requirements of keeping the nutritional value of dried carrots, low energy consumption and fast drying time, this study proposes a combination of osmotic dehydration and microwave vacuum drying.

The aim of this study was to improve microwave-assisted drying, in which microwaves bring the advantage of faster drying. The combination of microwave technology with low-temperature processing under vacuum has been studied by a number of researchers who have shown that microwave vacuum drying can be the process of choice to improve the quality of dried products with lower process temperature. Successful results have been reported for the microwave vacuum drying of several products such as orange powder, cranberries, potatoes, bananas, and carrots (Attiyate 1979; Kubota et al. 1992; Yongsawatdigul and Gunasekaran 1996; Drouzas and Schubert 1996; Tein et al. 1998).

Osmotic dehydration can be used to remove water from heat-sensitive products with low energy consumption at a low temperature. Since osmotic dehydration cannot remove moisture to a level that will prevent microbial growth, it is good as a preliminary partial dehydration step. While osmotic dehydration is a simultaneous process of water flow out and solid gain from osmotic agents, the gaining of osmotic agent can represent an added value in improving nutritional, sensorial and functional properties of the dried food.

In this study, the improvement of microwave-assisted drying with the combination of vacuum and osmotic treatment was investigated in terms of drying kinetics, drying models, energy consumption and quality aspects. The objective was to determine the effects of osmotic pretreatments followed by microwave vacuum drying at different input power level and power mode (continuous, 45 s on/15 s off and 30 s on 30 s off) for the dehydration of carrots.

MATERIAL and METHODS

Materials

Carrots of unknown cultivar were obtained from a local market and were cut into 10 mm sized cubes with a mechanical cutting tool. Carrots were stored at 4°C and were allowed to stand at room temperature (20 ± 1°C) 1 hour before the tests were started.

Initial properties measurement

The moisture content of the fresh carrots was determined by drying in a hot-air oven at 70°C for 12 hours (Ranganna 1986). The dielectric properties of fresh carrots were measured by an open-ended coaxial probe (Agilent-85070D, California) at a frequency of 2450 MHz. An Agilent network analyzer (Agilent-8722ES, California) was used to analyze the dielectric properties signal. The instrument was first calibrated using three different loads: (i) solid metal, (ii) air and (iii) distilled water at 20°C. The measurement was initiated by lightly pressing the samples against the flat face of the open-ended probe. The color of fresh carrots was measured using a chroma meter (Model CR-300X, Minolta Camera Co. Ltd., Japan).

Osmotic dehydration

In the process of osmotic pretreatment, 100 g of carrots were treated at room temperature (20°C) by placing them in a mixed osmotic solution of 50% wt/wt sugar concentration and 5% wt/wt salt concentration for 2 hours and 38 minutes, following optimum condition suggested by Changrue (2007). Since the results of the study by Singh et al. (1999) showed no significant difference among the ratios of sample to solution 1:4, 1:7, and 1:10 for the osmotic dehydration of carrot, all samples in this study were kept with a ratio of sample to solution of 1:5 (wt/wt). After osmotic treatment, the samples were dipped in water at ambient temperature (20°C), in order to remove the osmotic agents at the surface of the samples, gently blotted with tissue paper, and left for 15 minutes in ambient air in order to remove surface moisture. For each osmotic treatment, the 100 g sample was separated into 20 and a 80 g portions. The 80 g portion was used in microwave vacuum drying. The rest was analyzed to calculate water loss (WL), solid gain (SG) and dielectric properties following osmotic process.

Microwave vacuum drying

The variable power 0–750 W microwave vacuum dryer system used in this study was equipped to record drying product temperature and mass at every minute. The vacuum pressure was fixed at 8 kPa absolute pressure. Osmotically dehydrated carrot samples and fresh carrot samples were used to investigate the effect of osmotic pretreatment in microwave vacuum drying. The products were dried until the final moisture content reached 10% (wet basis). The dried samples were cooled to ambient temperature, packed and stored in a cold room at 3°C for water activity, shrinkage, rehydration, color, texture and sensory evaluation studies.

Empirical models

The experimental moisture content data was calculated using the equation:

$$MR = \frac{X - X_e}{X_o - X_e} \tag{1}$$

where MR is the moisture ratio, X is the moisture content at time t (kg/kg, dry basis), X_e is the equilibrium moisture content (kg/kg, dry basis), and X_o is the initial moisture content (kg/kg, dry basis). For the analysis, it was assumed that the equilibrium moisture content was equal to zero due to the vacuum condition. Three thin layer drying models were used in the analysis of the drying characteristics.

The Lewis (1921) model

$$MR = \exp(-kt) \tag{2}$$

The Henderson and Pabis (1961) model

$$MR = a^{*}\exp(-kt) \tag{3}$$

Page's (1949) model

$$MR = \exp(-kt^{n}) \tag{4}$$

They have been widely used due to their ease of use and their good fit with the observed data. The coefficient of determination (r^2) and root mean square error (RMSE) were used to evaluate the fit of each model in which RMSE was calculated using

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pred,i})^2\right]^{0.5} \tag{5}$$

where $MR_{\mathrm{exp,i}}$ is the experimental moisture ratio, $MR_{\mathrm{pred,i}}$ is the predicted moisture ratio, N is the number of data. The lower the calculated value of RMSE, the better the ability of the model to represent the observed data. This statistic has been widely used to select the best correlation between predicted curves and dried samples (Ozdemir and Devres 1999; Etekin and Yaldiz 2004; McMinn 2006).

Energy consumption

The energy consumption was calculated in terms of the specific energy consumption (SEC) with the following equation:

$$\text{SEC, J/kg water} = \frac{P \times t_{on}(100 - M_f)}{m(M_i - M_f)} \tag{6}$$

where P is the input power (W), t_{on} is the total amount of time "on" (s), M_{f} is the final moisture content (%, wet basis), M_{i} is the initial moisture content (%, wet basis), and m is the initial mass (kg)

Quality evaluation

The evaluation of the quality of the dried products was based on water activity, shrinkage, rehydration capacity, texture, color and sensory characteristics.

Water activity was measured using a water activity meter (Model 3 TE Series, Meyer Service & Supply, Ont., Canada). The dried samples were measured at 24.7°C which was the default setup of the device.

Shrinkage was calculated in terms of the percentage of volume change. Since the fresh carrot samples were cut into 10 mm cubes, the volume of a piece of fresh carrot was 1 cm^3. The volumes of dried samples were measured using a displacement method in toluene (Mohsenin 1986).

The rehydration capacity determines how the dried product reacts with moisture and is useful to determine, since, in most cases, dried carrots will be consumed in their rehydrated form. In this work, rehydration tests of dried samples were performed by the method recommended by Ranganna (1986). 150 g of distilled water was boiled in a 500 ml beaker. The water was brought to boiling point for 3 minutes then 5 g of dried samples were added to the boiling water for an additional 5 min. The rehydrated sample was transferred to a 7.5 cm Buchner funnel equipped with Whatman no. 1 filter paper. Water was drained by applying a gentle suction until there were no more drops from the funnel. The sample was then removed and weighed, and the rehydration ratio was calculated by using the following equation.

$$COR = \frac{m_{rh}(100 - M_{in})}{m_{dh}(100 - M_{dh})} \tag{7}$$

where COR is the coefficient of rehydration, m_{rh} is the mass of rehydrated sample (g), m_{dh} is the mass of dehydrated sample (g), M_{in} is the initial MC% (wet basis) of the sample before drying, and M_{dh} is the MC% of the dry sample (wet basis).

Texture characteristics were measured with an Instron Universal Testing Machine (Series IX Automated Materials Testing System 1.16). Compression tests were conducted using a 2 mm diameter plunger with a crosshead speed of 25 mm/min. The texture was evaluated in terms of firmness. The applied force (N) was plotted against deformation (mm). The slope of the force/deformation curve reflects elastic modulus and is often used as an index of firmness (Abbott 1999). The texture measurement was performed on the rehydrated product.

The surface color of dried samples was expressed in terms of color change and redness (*a*/*b*) by the same device used to measure the color of fresh carrots. Each reading provided a value for the color coordinates, L^*, a^* and b^*. The color change (ΔE) was calculated by the following equation.

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \tag{8}$$

where $\Delta L^* = L^*_{\text{sample}} - L^*_{\text{fresh}}$

$\Delta a^* = a^*_{\text{sample}} - a^*_{\text{fresh}}$

$\Delta b^* = b^*_{\text{sample}} - b^*_{\text{fresh}}$

The ratio (*a*/*b*) is a convenient way of reducing two parameters to one. The higher a/b ratio indicates more redness.

Since the dried carrots will mostly be consumed in rehydrated form, sensory tests were performed with the rehydrated samples. Sensory evaluations were done by a panel of 10 untrained judges evaluating two properties: taste and overall appearance. A rating using a hedonic scale ranging from "like extremely" to "dislike extremely" were given by judges. The range was later converted to numerical values from 9 (like extremely) to 1 (dislike extremely).

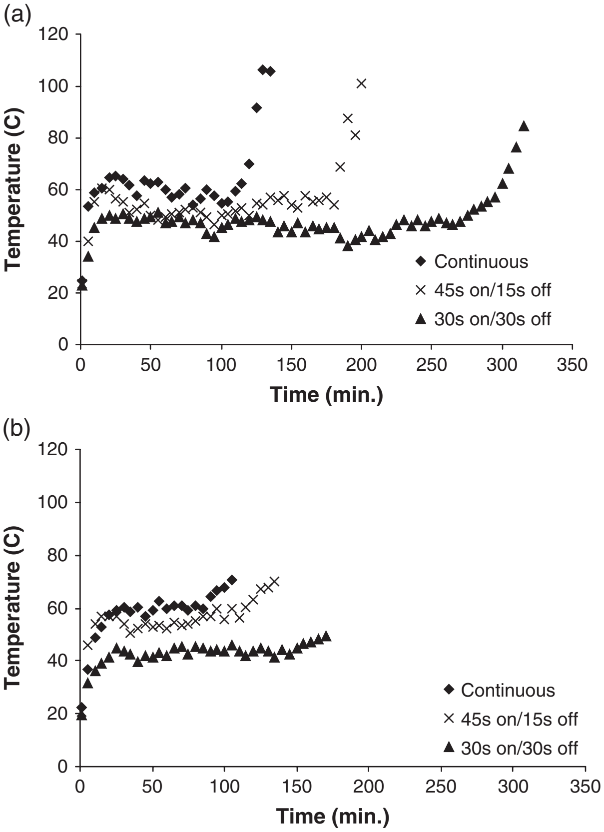

Fig. 1. (a) Temperature of microwave vacuum drying carrots at 1 W/g power with different power modes. (b) Temperature of osmotically dehydrated microwave vacuum drying carrots at 1 W/g power with different power modes.

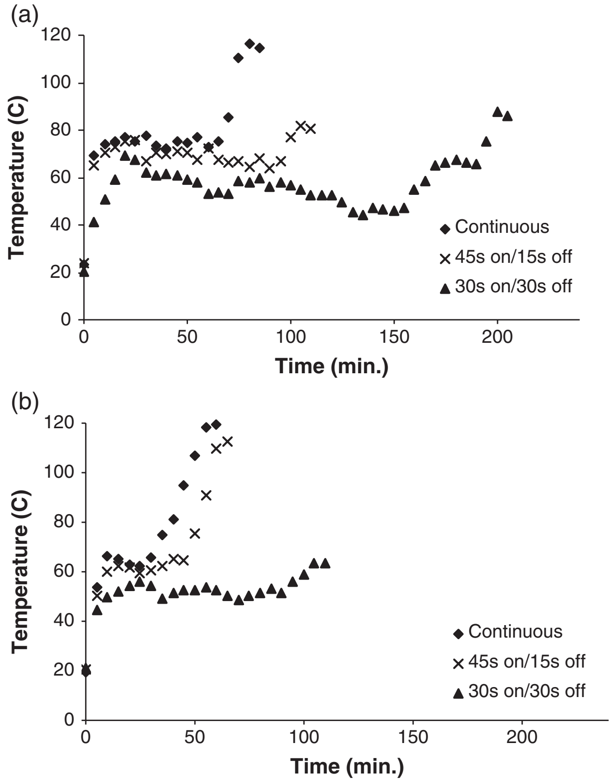

Fig. 2. (a). Temperature of microwave vacuum drying carrots at 1.5 W/g power with different power modes. (b) Temperature of osmotically dehydrated microwave vacuum drying carrots at 1.5 W/g power with different power modes.

Experimental design

The experimental design was a 2 × 2 × 3 factorial, with two osmotic treatment conditions, with or without, two input power levels (1 and 1.5 w/g) and three power application modes (continuous, 45 s on/ 15 s off and 30 s on/30 s off). The quality study data were subjected to analysis of variance (ANOVA) and the significance or non-significance of the variables was ascertained through Tukey HSD (honestly significant differences) multiple range test. All experiments were conducted in triplicate.

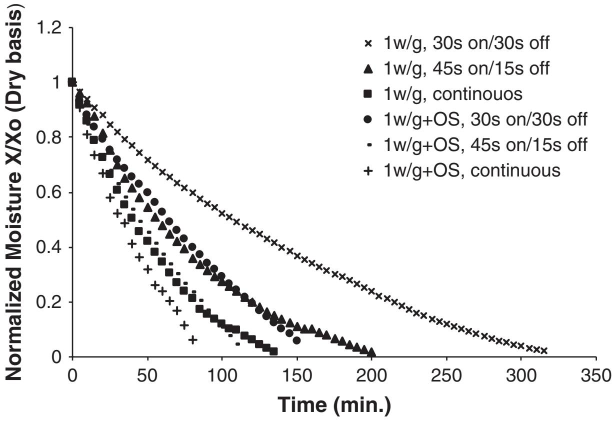

Fig. 3. Drying curves of carrots at 1 W/g with different power modes.

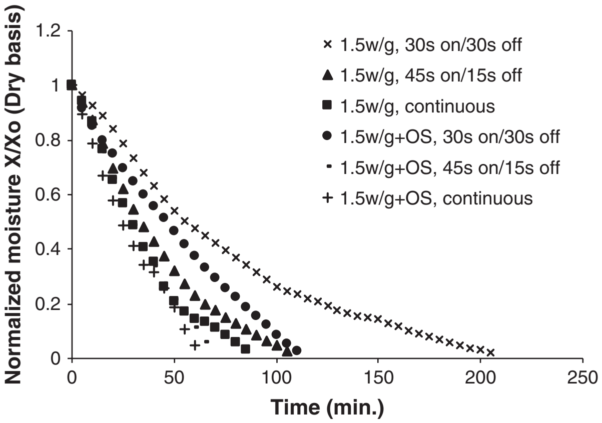

Fig. 4. Drying curves of carrots at 1.5 W/g with different power modes.

RESULTS and DISCUSSIONS

Osmotic dehydration

The moisture content of fresh carrots was 87.7% (wet basis). The initial dielectric constant (ε′) and dielectric loss (ε″) was 61.3 and 15.3, respectively. During the osmotic process, around 50% of water was removed from the fresh carrots, which resulted in an average moisture content of 67% (wet basis). The average dielectric properties of osmotically dried products were 55.3 and 24.9 for ε′ and ε″, respectively.

Drying kinetics of microwave vacuum drying

Drying kinetics of microwave vacuum drying (MVD) are presented in terms of the temperature of drying product, drying curve and drying time. The effects of pretreatment with and without osmotic dehydration, the differences of input power and power mode (on/off) are also discussed.

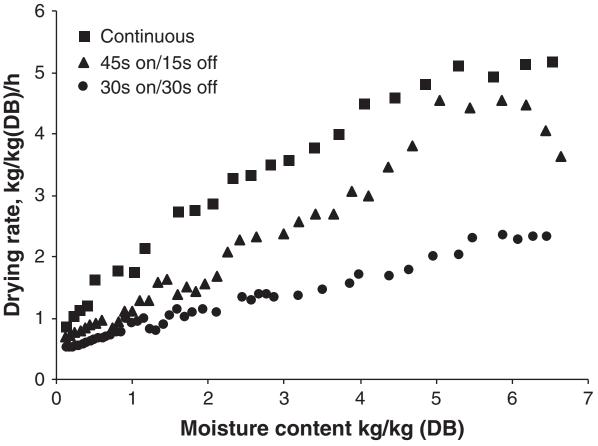

Fig. 5. Drying rates of microwave without osmotic pretreatment of carrots at 1 W/g with different power modes.

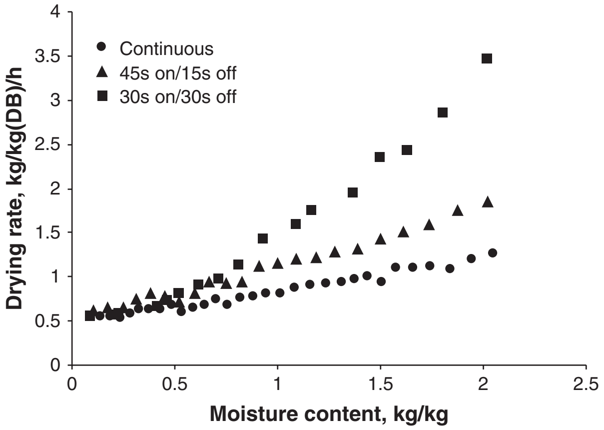

Fig. 6. Drying rates of microwave with osmotic pretreatment of carrots at 1 W/g with different power modes.

Temperature of drying product Figures 1a, b and 2a, b show the effect of osmotic pretreatment and power mode of microwave vacuum drying at input powers of 1 W/g and 1.5 W/g, respectively. There was no significant difference in product temperature during drying between samples with and without osmotic pretreatment. It might be due to the apparent balance between decreasing ε′ and increasing ε″ of osmotic treatment, which decreased the ability to couple with electromagnetic field, but increased the ability to dissipate the microwave energy within the product. The pulse mode (on/off) clearly showed an effect on drying product temperature. The longer inactive time (off) was able to decrease the drying product temperature to protect product quality. However, the pulse mode could not overcome the occurrence of excessive high temperatures in the drying process. The temperature at the end of the drying process was still high. This might be due to the heat build-up inside the material being higher than the required heat to evaporate the moisture at the last step of the drying process. So decreasing input power at the last stage of the microwave vacuum drying could be a way to control drying product temperature.

The effect of input power was in accordance with other studies (Lu et al. 1999; Boldor et al. 2005) in that the increased input power increased the drying product temperature. The average product temperature at input power of 1 W/g was 40-65°C, while the average for input power of 1.5 W/g was 45-80°C.

Drying curves, drying time and drying rates The osmotic process significantly affected drying curves and drying time for both input powers tested of 1 W/g as shown in Fig. 3 and 1.5 W/g in Fig. 4. The drying rates of microwave vacuum without osmotic pretreatment showed a short typical constant rate, which did not occur for the processes with osmotic pretreatment as seen in Figs. 5 and 6. These results are achieved because the water content of osmotically dehydrated product falls below the critical threshold level. Similar observation was made by Lewicki and Lenart (1992). Barbanti et al. (1994) also reported the absence of a constant rate period for fruits following osmotic dehydration. Beaudry et al. (2004) also found the absence of a constant rate period in microwave vacuum drying of osmotically dehydrated cranberries. Although the pulse mode of input power was able to decrease the temperature of the process as discussed above, it took longer to complete the drying process. Hence, the combination of energy consumption and end product quality should be considered in order to adopt proper parameters of operation in osmotically dehydrated microwave vacuum drying.

Empirical model of finish drying with microwave-vacuum

The wide applications of thin-layer models are due to their accurate prediction of drying performance and to their ease of use and lower data requirements. The constants of the models were acquired from nonlinear regression. The suitability of the models was validated by the RMSE and r^2, which were calculated using the observed data and predictive model. The constant values, RMSE and r^2, of the

Table 1. Coefficients and statistical analysis of thin-layer models for input power 1 W/g of microwave vacuum drying of carrots with different conditions.

		MVD			OS+MVD		
Model	Parameters	Continuous	45–15	30–30	Continuous	45–15	30–30
Lewis	k	0.0188	0.0131	0.007	0.023	0.017	0.012
	RMSE	0.03	0.04	0.04	0.03	0.04	0.04
	r^2	0.994	0.998	0.987	0.981	0.987	0.983
Henderson & Pabis	a	1.055	1.065	1.048	1.075	1.059	1.055
	k	0.0198	0.0139	0.007	0.0246	0.018	0.0128
	RMSE	0.03	0.02	0.04	0.031	0.04	0.04
	r^2	0.991	0.996	0.984	0.985	0.983	0.979
Page's model	k	0.008	0.00628	0.003	0.009	0.007	0.004
	n	1.195	1.1619	1.196	1.241	1.228	1.246
	RMSE	0.02	0.01	0.03	0.02	0.03	0.03
	r^2	0.997	0.998	0.991	0.993	0.992	0.991

Table 2. **Coefficients and statistical analysis of thin-layer models for input power 1.5 W/g of microwave vacuum drying of carrots with different conditions.**

		MVD			OS+MVD		
Model	Parameters	Continuous	45–15	30–30	Continuous	45–15	30–30
Lewis	k	0.027	0.0227	0.0137	0.03	0.026	0.017
	RMSE	0.06	0.04	0.04	0.06	0.07	0.06
	r^2	0.991	0.995	0.998	0.985	0.979	0.977
Henderson & Pabis	a	1.133	1.103	1.075	1.109	1.146	1.082
	k	0.031	0.025	0.0137	0.033	0.03	0.019
	RMSE	0.04	0.03	0.02	0.04	0.06	0.05
	r^2	0.985	0.991	0.996	0.979	0.968	0.971
Page's model	k	0.006	0.007	0.0059	0.009	0.004	0.004
	n	1.40	1.295	1.173	1.339	1.538	1.344
	RMSE	0.01	0.01	0.01	0.03	0.03	0.03
	r^2	0.999	0.999	0.998	0.991	0.996	0.989

models are presented in Tables 1 and 2 for the input powers of 1 W/g and 1.5 W/g, respectively. The comparison of RMSE among the models shows that Page's model presented the best fit in all cases of the study, including all input power levels, all power modes, and with or without osmotic pre-treatment with a RMSE of 0.01–0.03 and an r^2 of 0.990–0.999. This was another confirmation of the suitability of Page's model to microwave drying, which has been reported by Prabhanjan et al. (1995), Tulasidas et al. (1997), Kardum et al. (2001), and McMinn (2006).

The lack of fit in the middle period of the Lewis model, as shown in Fig. 7, agrees with the findings of Shivhare et al. (1994), who studied microwave drying of maize. They proposed using the surface moisture content instead of the equilibrium moisture content for the calculation of the moisture ratio (MR) to overcome the problem, but in the current study, the equilibrium moisture content was assumed to be zero due to the vacuum condition. Page's model was therefore the model of choice to fit the observed data for microwave vacuum drying.

Energy aspect

Energy consumption was presented in terms of specific energy consumption (SEC) in MJ/kg, which is related to the energy consumption per kilogram of water evaporated. The energy demand was considered only in the use of microwave and, thus, did not account for the energy for the vacuum used in the experiments. The calculated SEC of each combination of pre-treatment, input power and power mode are shown in Table 3. The results clearly showed a significantly lower SEC for the osmotically treated dried carrots when compared with drying without osmotic pretreatment. It can be concluded that the osmotic pre-treatment of carrot provided a great help to remove free water without affecting the diffusivity of the remaining drying process. So the drying time with osmotic pretreatment as discussed above was shorter, which resulted in lower energy demand to remove the rest of the moisture in the process. The interesting thing was that the lower input power did not mean lower energy consumption since higher input power yielded a shorter drying time. There was a significant contrast between with and without osmotic pretreatment on the effect of the microwave mode. The longer time "off" in the process of osmotic pretreatment showed the lower SEC, while drying without the osmotic pre-treatment tended to show the opposite trend. This might be the result of a longer process time from longer time "off" periods in drying without an osmotic pre-treatment. The general conclusion in terms of energy consumption of this study can be summarized in that osmotic pretreatment can help to reduce energy demand, the difference of input power levels did not affect energy consumption and the longer time "off" for drying following an osmotic pretreatment was able to decrease required energy.

Quality evaluation

Water activity (a_w) The water activity of all dried samples were found to be lower than 0.6 (Table 4). Foods having a water activity between 0.4 and 0.65 are considered to be shelf-stable dried foods (Raoult-Wack et al. 1991). No significant difference in water activity was found among

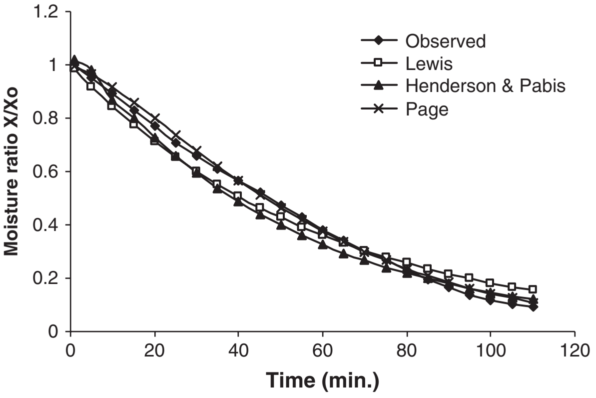

Fig. 7. **Comparison of observed MR in osmotically dehydrated microwave vacuum drying of carrots with the MR predicted by various models.**

Table 3. Comparison of specific energy consumption (SEC) with and without osmotic pretreatment of microwave vacuum drying of carrots.

MW power	MW Mode	Specific energy consumption (SEC), MJ/kg With osmotic	Without osmotic
1 W/g	Continuous	0.051	0.081
	45–15	0.050	0.091
	30–30	0.045	0.095
1.5 W/g	Continuous	0.056	0.081
	45–15	0.046	0.074
	30–30	0.050	0.094

all treatments. This was not surprising because the water activity is related to moisture content. The target moisture content of this study was 10% (wet basis) which was considered for the stabilization of the end product rather than measuring differences among treatments. Since the growth rate of molds, bacteria and yeast is not activated and enzymatic reactions are not promoted when the water activity is below 0.7 (Barbosa-Canovas and Vega-Mercado 1996), it should be noted that the 10% (wet basis) moisture content for the dried carrots provided a stable dried product in the safe water activity range.

Shrinkage The shrinkage is presented in Table 4 in terms of the percentage of volume change. Lower shrinkage occurred when the process was coupled with an osmotic pretreatment. The impregnation of sugar and salt from the osmotic agent to the carrots was able to strengthen the product's cell structure during drying. This study confirmed the decrease of shrinkage and lower collapse of cell structure which was reported by many researchers (Lozano et al. 1983; Nieto et al. 1998; Riva et al. 2005).

Table 4. Mean values of water activity and shrinkage for different combinations of pre-treatment, input power and power mode of carrots.

Treatment	Power	Mode	Water activity (A_w)	Change in volume (%)
With Osmotic	1 W/g	Continuous	0.55	40
		45–15	0.55	40
		30–30	0.55	40
	1.5 W/g	Continuous	0.55	40
		45–15	0.55	40
		30–30	0.53	40
Without Osmotic	1 W/g	Continuous	0.54	50
		45–15	0.52	50
		30–30	0.54	50
	1.5 W/g	Continuous	0.53	50
		45–15	0.53	50
		30–30	0.52	50

Rehydration capacity The rehydration capacity is presented in Table 5 and is expressed as a rehydration coefficient in which a higher value correlates with a higher capacity of rehydration. As observed in Table 5, the

Table 5. Tukey's test affected by pre-treatment, input power and power mode of carrots.

Treatment Mean	Input power Mean	Power mode Mean
Mean rehydration coefficient		
With osmotic 0.21^a	1 W/g 0.245^a	Continuous 0.250^a
Without osmotic 0.29^b	1.5 W/g 0.250^a	45s on/15s off 0.245^a
		30s on/30s off 0.245^a
Mean firmness		
With osmotic 8.97^a	1 W/g 11.14^a	Continuous 10.23^b
Without osmotic 14.33^b	1.5 W/g 12.14^a	45s on/15s off 11.76^a
		30s on/30s off 12.92^a
Mean color change (ΔE)		
With osmotic 25.64^a	1 W/g 26.46^a	Continuous 27.88^c
Without osmotic 28.93^b	1.5 W/g 28.10^b	45s on/15s off 27.52^b
		30s on/30s off 26.44^a
Mean redness (a/b)		
With osmotic 1.38^b	1 W/g 1.25^a	Continuous 1.32^c
Without osmotic 1.14^a	1.5 W/g 1.27^b	45s on/15s off 1.25^b
		30s on/30s off 1.21^a
Mean sensory (taste)		
With osmotic 3.82^a	1 W/g 4.67^a	Continuous 4.69^a
Without osmotic 5.62^b	1.5 W/g 4.77^a	45s on/15s off 4.72^a
		30s on/30s off 4.74^a
Mean sensory (over all appearance)		
With osmotic 7.53^a	1 W/g 5.75^a	Continuous 5.0^a
Without osmotic 3.13^b	1.5 W/g 4.92^b	45s on/15s off 5.1^a
		30s on/30s off 5.9^b

$^{a,\ b}$Mean with the same letter in the same column are not significantly different at the 0.05 level.

osmotic pretreatment and the level of input power significantly affected the rehydration but there was no influence from the two different power modes tested. In relation to the product's shrinkage, lower shrinkage promised to provide a higher rehydration capacity as was found by others in freeze drying (Liapis and Bruttini 1995; Beaudry et al. 2004). The result in this study was different. The presence in the carrots' void space of solids from the osmotic agents explains why the low shrinkage in this study provided lower rehydration capacity. There was no significant difference among the different types of power used.

Texture The results of texture measurements were plotted between the force (F) and deformation (D). The slope of the F/D plot was used to present the firmness in N/mm (Abbott 1999). Table 5 shows that osmotic pretreatment had a significant effect ($p < 0.05$) on firmness. The impregnation of solid content in the osmotic process made the end product softer than the treatment without osmotic pretreatment.

Color characteristics The color was presented in two ways, color change and redness (a/b) of end product. The results of color change are presented in Table 5, and show a significant influence ($p < 0.05$) of all factors studied; pretreatment, input power level and power mode. The fresh carrot was bright orange with an a/b ratio very close to 1. A higher a/b ratio of end product would therefore present more redness when compared with the fresh product. The osmotic pretreatment, higher input power level and longer power time "on" produced greater redness in the dried carrots. These effects would be expected because the temperature of the drying process directly affects the color characteristics. It was found in this study that the higher input power and longer power time "on" increased the product temperature, so the color would change due to the influence of input power level and duration of pulse power.

Sensory evaluation The sensory evaluation was conducted in terms of taste and overall appearance. The product after rehydration was tasted by 10 untrained judges. The product's score after drying with osmotic pretreatment was significantly lower than the others (Table 5). However, the whole response of the sensory evaluation fell between the scale of "dislike slightly" and "neither like nor dislike". It might be assumed that all judges relatively disliked the taste of rehydrated carrots. The time of rehydration in this study may have been too short. Furthermore, the rehydrated carrots used for this test were still salty. In terms of appearance, the rehydrated dried carrots that had been subjected to an osmotic pretreatment were significantly more appreciated than those without osmotic treatment. The browning attributed to longer time "on" and higher input power received the lowest acceptability.

CONCLUSIONS

There was no effect of the osmotic pretreatment on the product's drying temperature, while higher input power and longer time "on" had positive effects. The studied pulsing mode was not sufficient to control the product's drying temperature, hence lowering the input power at the last stage of the drying process should be considered.

Page's model showed the best fit with observed data for both cases with and without osmotic pretreatment. The drying constant (k) in the models showed that osmotic conditions in this study did not affect diffusivity of moisture in the microwave vacuum drying process.

The osmotic pretreatment coupled with microwave vacuum drying was able to decrease drying time and energy consumption in the production of dried carrots.

In terms of quality, osmotic treatment prior to microwave vacuum drying provided less shrinkage and rehydration capacity, but generated redness of the end product. Higher input power had positive effects on rehydration property and color change. A longer time "on" of pulse mode increased the color change.

ACKNOWLEDGEMENTS

The authors are grateful to the Postgraduate Education Research and Development Project in Postharvest Technology, Chiang Mai University, Thailand and the Natural Sciences and Engineering Research Council of Canada for the financial support.

REFERENCES

Abbott, J.A. 1999. Quality measurement of fruits and vegetables. *Postharvest Biology and Technology* 15: 207–225.

Attiyate, Y. 1979. Microwave vacuum drying: First industrial application. *Journal of Food Engineering* 51(2): 78–79.

Barbanti, D., D. Mastrocola and C. Severini. 1994. Air drying of plums: A comparison among twelve cultivars. *Science des Aliments* 14: 61–73.

Barbosa-Canovas, G.V. and H. Vega-Mercado. 1996. *Dehydration of Foods*. New York, NY: Chapman & Hall.

Beaudry, C., G.S.V. Raghavan, C. Ratti and T.J. Rennie. 2004. Effect of four drying methods on the quality of osmotically dehydrated cranberries. *Drying Technology* 22(3): 521–539.

Boldor, D., T.H. Sanders, K.R. Swartzel and B.E. Farkas. 2005. A model for temperature and moisture distribution during continuous microwave drying. *Journal of Food Process Engineering* 28: 68–87.

Changrue, V. 2007. Hybrid drying (osmotic, microwave-vacuum) of strawberries and carrots. Unpublished Ph.D. thesis. Montreal, QC: Department of Bioresource Engineering, McGill University.

Cui, Z.W., S.Y. Xu and D.W. Sun. 2004. Microwave-vacuum drying kinetics of carrot slices. *Journal of Food Engineering* 65: 157:164.

Drouzas, A.E. and H. Schubert. 1996. Microwave application in vacuum drying of fruit. *Journal of Food Engineering* 29(2): 203–209.

Etekin, C. and O. Yaldiz. 2004. Drying of eggplant and selection of suitable thin layer drying model. *Journal of Food Engineering* 63(3): 349–359.

Grabowski S. and M. Marcotte. 2003. Drying of fruits and vegetables and spices. In *Handbook of Postharvest Technology: Cereals, Fruits, Vegetables, Tea and Spices,* eds. Chakraverty, A., A.S. Mujumdar, G.S.V. Raghavan and H.S. Ramaswamy, 653–688. New York, NY: Marcel Dekker, Inc.

Henderson, S.M. and S. Pabis. 1961. Grain drying theory I: Temperature effect on drying coefficient. *Journal of Agricultural Engineering Research* 6: 169–174.

Kardum, J.P., A. Sander and D. Skansi. 2001. Comparison of convective, vacuum and microwave drying chlorpropamide. *Drying Technology* 19(1): 167:183.

Kubota, K., C. Omae, J.D. Heng and Y. Hagura. 1992. Studies on microwave vacuum drying phenomena and models of potato. *J. Hiroshima Daigaku Seibutsu Seisan Gakubu Kiyo* 31(1): 37–43.

Lewis, W.K. 1921. The rate of drying solid materials. *Journal of Industrial Engineering* 13: 427–443.

Lewicki, P. and A. Lenart. 1992. Energy consumption during osmo-convection drying of fruits and vegetables. In *Drying of Solids*, ed. A.S. Mujumdar, 354–366. New York, NY: International Science Publishers.

Liapis, A.I. and R. Bruttini. 1995. Freeze drying. In *Handbook of Industrial Drying*. 2nd edition. ed. A.S. Mujumdar, 309–343. New York, NY: Marcel Dekker, Inc.

Lin, T.M., T.D. Durance and C.H. Scaman. 1998. Characterization of vacuum microwave, air and freeze dried carrot slices. *Food Research International* 31(2): 111–117.

Lozano, J.E., E. Rostein and M.J. Urbicain. 1983. Shrinkage, porosity and bulk density of foodstuffs and changing moisture contents. *Journal of Food Science* 48: 1497–1502.

Lu L., J. Tang and X. Ran. 1999. Temperature and moisture changes during microwave drying of sliced food. *Drying Technology* 17(3): 413–432.

McMinn, W.A.M. 2006. Thin-layer modeling of the convective, microwave, microwave-convective and microwave-vacuum drying of lactose powder. *Journal of Food Engineering* 72: 113–123.

Mohsenin, N. N. 1986. Physical properties of plant and animal materials: structure, physical characteristics, and mechanical properties. Gordon and Breach, New York.

Mulet, A., A. Berna, S. Rosello and J. Canellas. 1993. Analysis of open sun drying experiments. *Drying Technology* 11(6): 1385–1400.

Nieto, A., D. Salvatori, M.A. Castro and S.M. Alzamorz. 1998. Air drying behavior of apples as affected by blanching and glucose impregnation. *Journal of Food Engineering* 36: 63–79.

Ozdemir, M. and Y.O. Devres. 1999. The thin layer drying characteristics of hazelnuts during roasting. *Journal of Food Engineering* 42: 225–233.

Page, G. 1949. Factors influencing the maximum rates of air drying shelled corn in thin layers. Unpublished M.Sc. thesis. West Lafayette, IN: Purdue University.

Prabhanjan, D.G., H.S. Ramaswamy and G.S.V. Raghavan. 1995. Microwave-assisted convective air drying of thin layer carrots. *Journal of Food Engineering* 25: 283–289.

Ranganna, S. 1986. Handbook of Analysis and Quality Control for Fruit and Vegetable Products. New Delhi, India: Tata McGraw-Hill Publishing Company Ltd.

Raoult-Wack, A.L., S. Guilbert, M. Le Maguer and G. Rios. 1991. Simultaneous water and solute transport in shrinking media – Part 1. Application to de-watering and impregnation soaking process analysis (osmotic dehydration). *Drying Technology* 9(3): 589–612.

Ratti, C. and A.S. Mujumdar. 1997. Solar drying of foods: Modeling and numerical simulation. *Solar Energy* 60(3–4): 151–157.

Riva, M., S. Campolongo, A.A. Lava, A. Maestrelli and D. Torriggiani. 2005. Structure-property relationships in osmo-air-dehydrated apricot cubes. *Food Research International* 38: 533–542.

Shivhare, U.S., G.S.V. Raghavan and R.G. Bosisio. 1994. Modelling the drying kinetics of maize in microwave environment. *Journal of Agricultural Engineering* 57(3): 199–205.

Singh, S., U.S. Shivhare, J. Ahmed and G.S.V. Raghavan. 1999. Osmotic concentration kinetics and quality of carrot preserve. *Food Research International* 32: 509–514.

Tein, M.L., D.D. Timothy and H.S. Christine. 1998. Characterization of vacuum microwave, air and freeze dried carrot slices. *Food Research International* 31(2): 111–117.

Tulasidas, T.N., C. Ratti and G.S.V. Raghavan. 1997. Modelling of microwave drying of grapes. *Canadian Agricultural Engineering* 39(1): 57–67.

Yongsawatdigul, J. and S. Gunasekaran. 1996. Microwave-vacuum-drying of cranberries: Part I: Energy use and efficiency. Part II: Quality evaluation. *Journal of Food Processing & Preservation* 20(2): 121–156.